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Research article

A comparative total cost of ownership analysis of heavy duty on-road and off-road vehicles powered by hydrogen, electricity, and diesel

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HIGHLIGHTS

- Several FCEVs are cost competitive with ICEVs under base conditions, but not BEVs.
- A fossil tax significantly accelerates the year that FCEVs become competitive with ICEVs.
- A high purchase grant and a low hydrogen fuel price are key to reducing FCEV TCO.
- By 2050, several FCEV scenarios will have a TCO below ICEVs, and even some BEVs.
- BEVs incur fewer financial costs than FCEVs but may suffer indirect costs from payload losses and long charging times.

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ABSTRACT

This study investigated the cost competitiveness, using total cost of ownership (TCO) analysis, of hydrogen fuel cell electric vehicles (FCEVs) in heavy duty on and off-road fleet applications as a key enabler in the decarbonisation of the transport sector and compares results to battery electric vehicles (BEVs) and diesel internal combustion engine vehicles (ICEVs). Assessments were carried out for a present day (2021) scenario, and a sensitivity analysis assesses the impact of changing input parameters on FCEV TCO. This identified conditions under which FCEVs become competitive. A future outlook is also carried out examining the impact of time-sensitive parameters on TCO, when net zero targets are to be reached in the UK and EU. Several FCEVs are cost competitive with ICEVs in 2021, but not BEVs, under base case conditions. However, FCEVs do have potential to become competitive with BEVs under specific conditions favouring hydrogen, including the application of purchase grants and a reduced hydrogen price. By 2050, a number of FCEVs running on several hydrogen scenarios show a TCO lower than ICEVs and BEVs using rapid chargers, but for the majority of vehicles considered, BEVs remain the lowest in cost, unless specific FCEV incentives are implemented. This paper has identified key factors hindering the deployment of hydrogen and conducted comprehensive TCO analysis in heavy duty on and off-road fleet applications. The output has direct contribution to the decarbonisation of the transport sector.

1. Introduction and background

Increasing concern regarding climate change has led to efforts to reduce global carbon emissions. Many countries and regions such as the UK and the EU have set a target of net zero greenhouse gas emissions by 2050, promoting the growth of renewable energy to decarbonise polluting sectors like the transport industry. In 2019 transport contributed most (22%) to total UK greenhouse gas emissions, within which heavy duty vehicles (HDVs) released a disproportionately high quantity of CO_2 emissions considering their share in total surface transport, resulting in the need for more sustainable solutions [1]. For example, in 2019 heavy goods vehicles made up 5% of the total road traffic but released 17% of the total CO2 emissions [1].

To help achieve the 2050 targets, ultra-low and zero emission vehicles (ULEVs and ZEVs) are essential. ULEVs are vehicles emitting <75g CO_2 per km from their tailpipe, though this may fall to <50g to acknowledge improvements in technology [3]. ZEVs include fuel cell electric vehicles (FCEVs) and battery electric vehicles (BEVs) respectively. BEVs appear to have the head start in the automotive industry with ~15,000 BEVs newly registered in the UK in January 2022; making up 12.5% of all new registrations that month, and having the largest annual increase in 2021 despite the impacts of Covid-19 [4]. For FCEVs,

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only 68 were sold in 2019, suggesting BEV uptake is more likely to dominate the passenger car sector, though BEVs did enter the market first [5]. For HDVs however, progress is slow due to the constraint of energy density for current battery technology.

Challenges for widespread use of BEVs in HDV applications include energy density, weight compounding, material shortages, and long recharging times which can negatively impact service provision and productivity. FCEVs for HDVs on the other hand, have advantages of faster refuelling, increased range, sustained operation under extreme conditions, and low fuel cell degradation, unlike lithium-ion batteries [6, 7]. One impact of these batteries in BEV use is shown in the electric trucks by Daimler, which lead to a 1400–1800 kg weight increase compared to their diesel versions [8]. This issue is minimised for LDVs with lower range demands but avoided for FCEVs using hydrogen with an energy density of 33.6 kWh/kg. For FCEVs, increases in range are compensated by basic vehicle adaptations. BEVs also rely on costly materials like lithium and scarce ones like cobalt (listed on the 2020 EU Critical Raw Materials List) for their manufacture and [9] state that to supply the EU economy in 2030, for BEVs and energy storage, 18 times more lithium and 5 times more cobalt is needed. Since ~64% of the world's cobalt is sourced from the Democratic Republic of Congo using unsustainable practices, this could cause supply chain issues. FCEVs also face criticism from sceptics regarding their availability, pointing out a current lack of infrastructure which presents a significant barrier to uptake. As a result, back-to-base (B2B) fleet applications ensure a consistent hydrogen demand is maintained, helping improve economics.

[10] found in 2020, BEVs gave lower life cycle costs by 79–97% for a light duty vehicle (LDV) fleet, compared with FCEVs. However by 2040, these gaps will likely close due to cost reductions from scale up, as FCEVs showed advantages in the majority of vehicle classes, particularly larger vehicles. The paper predicted the existence of a LDV market allowing for coexistence of FCEVs and BEVs [11]. investigated fleet use to support diffusion and early adoption of alternative fuel vehicles since they give quick insights into the operation and barriers to implementation. Often, fleet vehicles are characterised by high mileage, central or B2B refuelling, and predictable duty cycles. Therefore increased FCEV deployment could be achieved through conversion of captive fleets unsuitable for BEVs, where a consistent and reliable hydrogen demand is provided.

[6] compared the TCO of FCEV cars, trucks and buses to other powertrains. FCEVs were the least competitive in forecourt and centralised production compared to BEVs, plug in hybrid EVs (PHEVs) and ICEVs [12]. investigated cost competitiveness of 3 FCEV heavy-duty trucks and all truck segments showed great potential for cost reduction, with economies of scale vital between 2023 and 2030. Although these vehicles will be 11–22% more expensive than diesel in 2023, they will be cheaper than BEVs and showed promise of competitiveness with diesel by 2030. TCO was lower for long and medium haul FCEV trucks compared to BEV, highlighting advantages in high range demands [13]. and [14] carried out similar TCO studies. Here, both found BEVs best suited for short range applications whilst FCEVs became the lowest cost option for heavier vehicles with high range demands where BEVs require long recharging times. In the studies, hydrogen and electricity prices were the most influential parameter for all TCO's, and these fuels could reach parity with diesel by 2025 under specific conditions and a high diesel price [15]. compared FCEV trucks in a current scenario, a modest future cost improvement, and strong future cost improvement, with TCO lowest with the strongest improvements. Insights agree with other work, highlighting the high contribution of fuel cost on the TCO. They concluded FCEV trucks can be economically feasible but are strongly influenced by hydrogen price and vehicle CAPEX [16]. also found ZEV TCO was sensitive to mileage due to lower operating costs. BEV urban logistic vehicles became more competitive than ICEVs once exceeding an annual mileage of 17,000 miles. This mileage influence did not extend to FCEVs using 350 bar hydrogen, though the impact of congestion charges and grants had a large effect on the incentivisation of ZEVs.

Many studies in literature focus on one vehicle type only and fail to consider a range of zero-emissions fuels and powertrains. Many focus on developing or new low and zero emission powertrains and compare these directly to conventional equivalents in terms of TCO. However, two zero emission solutions (BEV and FCEV) are rarely compared directly. These studies are now growing in number due to the development in alternative transport technologies and an increased push towards low carbon fuels by government policy, but the majority focuses on LDVs. This study investigates the TCO of a mixed fleet of on-road and off-road FCEVs against BEV *and* ICEV equivalents using a captive fleet (Leeds City Council (LCC)) and an off-road fleet (Leeds Bradford Airport (LBA)) as the case studies. A unique feature of this work lies in the integration of on and off-road vehicles that can be scaled to meet demands for TCO analysis of different fleets. The study also examines the potential of hydrogen and fuel cell technology as a key enabler in the decarbonisation of transport, and examines the feasibility of FCEV deployment in heavy duty off-road transport fleets. Also, gaps exist in literature regarding economic assessments for a much wider range of vehicles. This work considers both heavy duty city buses, trucks, tippers and refuse collection vehicles, alongside light duty forklifts respectively. It also offers flexibility to allow similar insights to be generated for other regions.

The study includes sensitivity analysis on present-day results, with variation of input parameters to assess impacts on TCO and identify conditions under which FCEVs are most cost effective. TCO is also examined across a longer timescale from the 2021 to 2050, to assess the impact of time-sensitive parameters on the cost competitiveness of FCEVs. The novelty of this paper lies in that the paper addresses a key question for the deployment of hydrogen in transport: what are the key parameters that can either hinder or promote the deployment of hydrogen in heavy duty on-road and off-road vehicles. In other words, what are the parameters and conditions that can boost the cost competitiveness of hydrogen FCEVs. The comprehensiveness of the analysis and the inclusion of multiple hydrogen production pathways provide much needed cost information and knowledge for decarbonising heavy duty transport.

2. Methods and data

2.1. Structure of the total cost of ownership model

TCO analysis is a useful tool for vehicle owners and operators to compare the costs of different vehicles and identify the most economical option. Since comparing multiple costs can quickly become a complex procedure, TCO compares one single figure on a like-for-like basis. This process involves summing purchase and operating costs and dividing by distance travelled giving a single cost typically reported in cost per km.

Figure 1 shows the structure of the TCO model used. Within this, optional input conditions are added to increase flexibility and account for potential changes resulting from government and policy decisions.

*Although TCO can include vehicle parking, most analyses exclude this. This work is focused on B2B fleet vehicles where parking is not an issue, so this is not considered here. However, the model does have potential to include this parameter if needed.

2.2. Fuel supply and costs

As LBA operate their fleet by purchasing diesel on an ad-hoc basis for a fixed price inclusive of delivery, the same approach was used here [32]. reported average diesel prices in 2019 at approximately £1.30/L, inclusive of tax. However, due to the impacts of both Covid-19 and the Ukraine war on energy security, a 25% premium has been added to this to reflect current UK prices, giving a final delivered diesel price of £1.60/L.

Since hydrogen costs vary greatly depending on the production route, three options are considered.

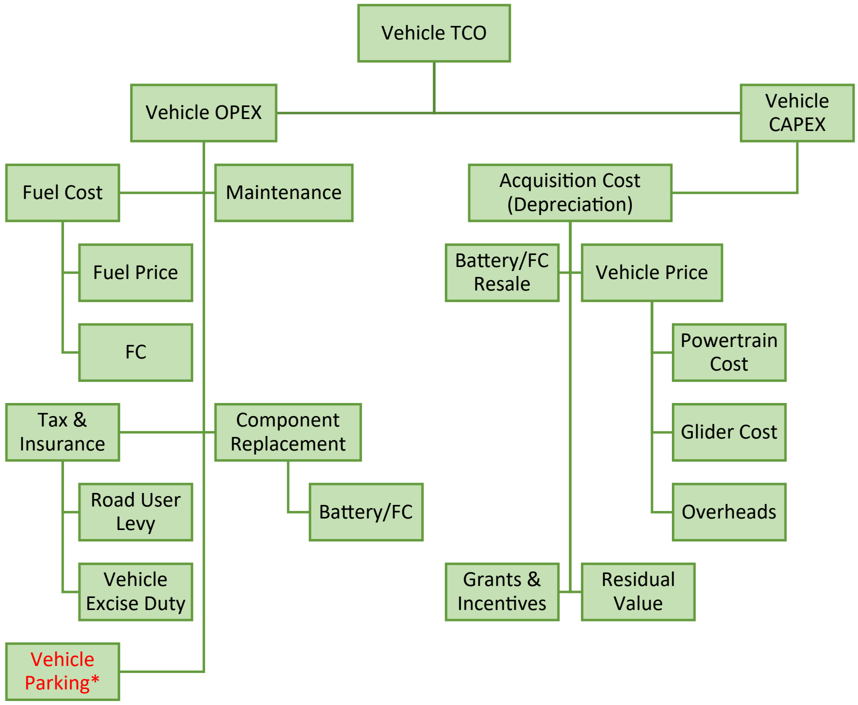

Figure 1. Breakdown of the TCO components included in the model.

1. Steam Methane Reforming (SMR).
2. SMR with Carbon Capture and Storage (SMR with CCS)
3. Polymer Electrolyte Membrane (PEM) Water Electrolysis.

In this work hydrogen production is assumed to be centralised, taking place around the Tees Valley region where roughly 50% of UK hydrogen production currently takes place and where many experts have identified as a potential hydrogen hub for future projects [48]. Current costs for hydrogen production in this work were sourced from [18] at £1.59/kg for SMR and £1.74/kg for SMR with CCS respectively. Centralised production is generally characterised by lower production costs but faces a trade-off with higher distribution costs since the hydrogen must be transported over a greater distance to its point of end use. In this case, the hydrogen is transported an assumed distance of 200 km to its point of use in the fleet.

The distribution is carried out using the 3 most common methods available today; compressed gaseous pipelines, pressurised tube trailers (TT), and liquid tankers (LT). For these delivery routes, the costs of conditioning such as compression and liquefaction were calculated based on the electricity consumption using an assumed price of £0.144/kWh for grid electricity in 2021, based on average prices for the UK mix, taken from [20]. In addition to conditioning, costs of diesel consumption in TT and LT were included, along with vehicle OPEX which was assumed to be 5% of the CAPEX, taken from [17] respectively.

Similar to grey and blue hydrogen production, the costs of green hydrogen from water electrolysis using wind, solar, and hydropower vary depending on several factors. These are mostly dominated by electrolyser OPEX, which in this work equated to £38/kW based on [49], and the demand for grid electricity in the event of shortages in renewable energy generation. Additional costs are also associated with water desalination which employs reverse osmosis, requiring 3–4 kWh of electricity and costing approximately £1.10 per m^3 water [24]. The impact of this on the final hydrogen price however is low and equates to roughly £0.01/kg H_2. Although desalination is not always necessary in areas with plentiful water supply, it was included in this work to offer a conservative estimate. For this study, wind power was chosen as it is the dominant renewable power in the UK [19]. For landlocked countries in the EU that do not have the opportunity to use offshore wind power to generate energy, solar power is likely to be used instead. UK green hydrogen is produced on-site by.

1. **225 kW & Grid:** A 225 kW wind turbine (such as the one currently used by a hydrogen refuelling station in Sheffield, UK) installed on-site, generating electricity from renewable power with any excess electricity required to be sourced from the UK grid.
2. **100% RES**: 100% renewable electricity from wind power.
3. **50-50 Split:** A 50-50% split in which half of the electricity for hydrogen production is sourced from wind power, and the other half is sourced from the UK grid at a cost of £0.144/kWh in 2021.

Electricity generation for BEVs mirrors the electrolysis scenarios above and is carried out on-site, but also includes rapid chargers using grid electricity. The price of electricity from these chargers comes at a premium for their convenience and is based on reported costs in the UK at £0.24/kWh [50]. In this work, all electricity generation from renewable sources is considered free of charge. In many instances, instead of being curtailed during periods of lower demand, surplus renewable power can be converted to hydrogen and stored for long periods of time until demand outweighs supply, or like electricity it can be used directly in transport applications. This is one of the main advantages of hydrogen as an energy carrier. Only additional electricity required (where renewable generation cannot provide the full demand) is paid for.

A summary of all fuel production and distribution pathways is given in Figure S1 in the Supplementary Materials whilst the final delivered costs of all fuels are given in Table 1.

Comparing these estimates to those in literature can be challenging as fuel costs vary widely due to the specific conditions used, such as production capacity, grid price, distribution distances, and production efficiencies. However, several reports offer estimates which align with those above, indicating the figures are reasonable. Costs of green hydrogen pathways reported by [60] align with the highest costs recorded coming from decentralised production using grid-dependent electrolysis ranging from £7.6–14.1/kg H_2. Similarly [62], report figures of between €6.5–14/kg H_2 for European green hydrogen, whilst [63] offer lower

Table 1. Final delivered fuel costs used in this study.

	Delivered Fuel Cost:			
Fuel Scenario:	Cost (£):	Unit:	Cost (£):	Unit:
Diesel	1.60	L	0.16	kWh
H_2 – SMR (Pipeline)	2.18	kg	0.07	kWh
H_2 – SMR (Tube Trailer)	6.41	kg	0.19	kWh
H_2 – SMR (Liquid Tanker)	6.99	kg	0.21	kWh
H_2 – CCS (Pipeline)	2.33	kg	0.07	kWh
H_2 – CCS (Tube Trailer)	6.56	kg	0.20	kWh
H_2 – CCS (Liquid Tanker)	7.14	kg	0.21	kWh
H_2 – Electrolysis (225 kW)	7.52	kg	0.23	kWh
H_2 – Electrolysis (100 RES)	2.26	kg	0.07	kWh
H_2 – Electrolysis (50-50 Split)	5.86	kg	0.18	kWh
Electricity – Electrolysis (225 kW)	0.00	kWh	0.00	kWh
Electricity – Electrolysis (100% RES)	0.00	kWh	0.00	kWh
Electricity – Electrolysis (50-50 Split)	0.08	kWh	0.08	kWh
Electricity – Electrolysis (Rapid Charger)	0.24	kWh	0.24	kWh

estimates of \$3–6.5/kg H_2. In contrast, several studies highlight the lowest cost pathways come from centralised grey hydrogen using SMR as it is a mature technology and makes use of cheaper fossil fuels [63] Studies also show that distribution using pipelines is often the most cost effective form of delivery for hydrogen over short distances, which agrees with the figures in this study respectively [61]. One takeaway from Table 1 is the fact that in general, the price of hydrogen is greater than electricity per kWh. Aside from rapid chargers, electricity is significantly cheaper to source and is partly due to the fact that the electricity scenarios do not incur any conditioning costs, nor do they require distribution since production takes place on-site.

For both green and liquefied hydrogen in particular which incur these additional costs and show the highest prices per kWh, it presents an obstacle for FCEV uptake which needs to be addressed in order to encourage users to transition to hydrogen vehicles and support the goal of net zero. One solution to do this is to incentivise the production of hydrogen to increase its capacity and bring costs down through economies of scale. This is being targeted by increasing the low carbon hydrogen capacity in the UK from 5 to 10 GW by 2030 and introducing subsidies which promote low carbon hydrogen production further. An example of this is the Clean Hydrogen Subsidy Scheme which was introduced in the UK in July 2022 and aimed to help fund the first 1 GW of green and 1 GW of blue hydrogen projects using a contracts for difference style approach [51]. Others have been introduced which will encourage green hydrogen production and support cost drops in the future. In addition to scale up of production, electrolyser efficiency is expected to increase through scale up and learning-by-doing as more projects are brought online, and other incentives may be used to promote the production and use of green hydrogen such as regulations on CO_2 pricing, tax reliefs and discounts, for example. Later in this work a sensitivity analysis investigates the impact of a 20% hydrogen price drop on vehicle TCO respectively.

2.3. Input parameters and variables

Variable inputs chosen are fuel consumption, electricity price, electrolyser efficiency, hydrogen drivers, and diesel deterrents. Rationale and justification for each variable input are given in this section respectively.

Fuel cost is a major contributor to TCO so fuel consumption (FC) figures should be representative of the vehicles used under real conditions. Figures for ICEVs used the best diesel engines in 2021 and were sourced from published data by manufacturers and does not consider significant future improvements. This is because the technology is already mature and due to be phased out, along with the fact that diesel engines are not the focus of this study. For those BEVs and FCEVs available on the market today, FC data was sourced from [17], manufacturers, and OEMs and is inclusive of battery and fuel cell efficiency. In the cases where FC data was not available, estimates were made based the performance of prototypes and vehicles of a similar performance and specification. For example, for FCEV cars the FC of the Toyota Mirai is available and reported at 0.55 kg H_2/100km. In the future, expected developments in technology and efficiency will lead to improvements in the vehicle FC. To account for this, work by [21] was used as a guideline and a 5% drop in consumption every 5 years is assumed which is in line with this work. FC for all vehicles is given in Table S1 respectively.

It should be made clear that this work uses a constant FC from manufacturers reported figures which does not account for the changes in vehicle payload. The author acknowledges the fact that in reality FC is a function of payload which will greatly fluctuate with vehicle weight and driving conditions, and this presents a limitation to the study which must be conceded. Similar to payload, temperature is another factor which impacts the fuel/energy consumption of vehicles. Cold weather has been proven to significantly reduce the efficiency of BEVs, increasing their energy consumption by as much as 50% due to the increased demand for cabin heating and the prevention of powertrain freezing [52]. Although the impacts of this on ICEVs and FCEVs are much lower, for BEVs this factor should be acknowledged as it can have non-financial knock-on effects. For example, if a BEV's range is reduced during cold periods, the requirements for charging increase which can lead to greater downtime and a less productive fleet. Also, if a larger battery is installed to compensate for these cold-weather losses, this can also lead to issues in terms of payload which should be acknowledged. BEVs often face this criticism from sceptics regarding a potential loss of payload as a result of the large batteries required to achieve a comparable driving range to ICEVs and FCEVs. For example, tipper trucks in this work are based on the Renault D Wide ZE, with a 265 kWh battery weighing ~1700 kg. Assuming cold weather leads to battery efficiency falling 50%, double the battery capacity is required to carry out the same functions and this extra 1700 kg will now reduce the available payload. At approximately 12t, the payload decreases to ~10.3t (~15%) after the addition of this battery, reducing the vehicle's productivity. In this case, if a fleet consisting of 7 tippers was used, the total loss in payload is equivalent to ~12t. Now, to compensate for this loss, another vehicle must be purchased, offsetting any cost savings seen by BEVs, and potentially making FCEVs more cost effective solutions.

For this study the impacts of temperature on powertrain efficiency are considered outside of the scope, though they should be considered in future work along with payload effects on FC outlined earlier. Both of these omissions are factors which could be included to generate a more accurate result and are therefore considered areas of improvement listed in 'Limitations and Recommendations' in Section 4 respectively.

After FC, the second variable input parameter is the electricity price. The UK grid electricity price is unlikely to remain fixed between 2021-2050. With multiple sources and dynamic combinations making up the mix, it is difficult to predict the future composition and its price. However, prices have increased due to the ongoing impacts of Covid-19 and the recent events in Russia/Ukraine which have negatively affected natural gas availability, as well as the ongoing shrinkage of fossil fuel reserves which increase the demand for renewable energy, contributing a greater share of total power generated. As a result, electricity prices are predicted to increase for the foreseeable future and to account for this, this work has assumed a 10% increase in electricity cost every 5 years, starting at £0.144/kWh in 2021 and rising to £0.255/kWh in 2050 [22]. Table S2 shows the electricity price profile to 2050.

Equipment efficiency is expected to improve through learning-by-doing, scale up, and future advances in technology. Studies suggest proton exchange membrane (PEM) electrolysers have energy efficiencies between 60-80% [23] while the IEA [24] estimate electrical efficiencies of 56–60%. This work assumed a conservative electrical efficiency of 65% in 2021, increasing to 75% in 2025 and 85% in 2030, which is in alignment with future predictions by [25]. After 2030, the rate of efficiency increase slows and by 2040 reaches its peak of 90%.

Tools for hydrogen and electric incentivisation, and diesel discouragement are also variable. Purchase grants for Zero Emission Vehicles (ZEVs) alleviate high upfront costs and encourage uptake in early adoption stages, whilst an additional fossil tax on diesel pushes motorists away from fossil-based fuels to consider a switch to sustainable ones. Both are discussed later in Section 2.9.

In addition to time-sensitive input parameters, the future value of money must also be discounted to 2021 costs. This work discounts future costs using a real discount rate of 0.7%, which was taken from UK government from March 2021 respectively [26]. Although a fairly low rate, the impacts of using a higher rate are not expected to cause significant changes to the conclusions of this work since the only future costs being discounted in this work are from component replacements and vehicle residual value, both of which are included in FCEV and BEV TCO and shown to have a small impact on total costs in comparison to other components such a fuel costs, for example.

2.4. Fleet composition, base case conditions, and vehicle purchase costs

Tables 2 and 3 give an overview of the vehicles and base case conditions of the study, including mileage and fuel consumption. All vehicles operate on a 10-year ownership period (loosely based on the average lifetime of a HDV in the UK, at 12 years) and are not subject to any financial incentives or deterrents [27]. report PEM FCs have a 20% recoverable value, whilst [28] said they expect batteries to be repurchased for 30% of their original cost. As a result, these residual value (RV) figures have been applied here. The RV for the remainder of the vehicle (glider and remaining powertrain) will vary in reality depending on its condition but is given a modest value of 25% in this work since the ownership period is only 10 years with one owner. This ownership period is relatively short when compared to vehicles used outside of fleet applications which are typically resold and enter a second life with another owner.

The mileage of each vehicle in Table 3 is based on real data across 2018–2020 prior to Covid-19 shown in Table S3 in the Supplementary Materials. This was reported by existing fleets, company fleet reports, and literature studies. This mileage data is not specific to one particular region or fleet and is therefore considered ‘generic’. In all references in Table S3, the vehicle operating frequency was omitted from the mileage figures, so this work estimates daily mileage with the assumption of 350 days of vehicle operation per year, which is reasonable for fleet vehicles characterised by high usage rates. For vehicles that have multiple annual mileage figures, average values are used.

Aside from the mileage, all other inputs including purchase grants, taxes, component costs, and energy prices are fixed using 2021 data. These are later adjusted in a sensitivity analysis and future outlook to account for expected technological improvements and policy changes over time.

The automotive market currently lacks a broad inventory of BEVs and FCEVs. Whilst some vehicles have been on the market for a while and have established purchase prices, others do not have ZEV versions available yet (particularly in the HDV sector) which means estimates of their purchase prices have to be made. These are based on predictions by manufacturers for prototype vehicles which haven’t yet entered the market, as well as estimates from various technology reports, for example. Some sources offer accurate purchase prices, whilst for other vehicles not available, purchase prices are estimated. These prices are given in Table 4 respectively. In order to save space, the full list of the sources used to derive these estimates is provided in Table S4 in the Supplementary Materials respectively.

Table 2. Baseline conditions.

Condition:	Baseline Value:
Modelling Year	2021
Quantity of Each Vehicle in Fleet	1
Ownership Period (years)	10
Fossil Tax?	No Tax Applied
BEV/FCEV Purchase Grant?	No Grant Applied
Road Use Tax?	No Tax Applied
Battery and/or FC RV	20% and 30%
Glider and Powertrain RV	25%

Due to their sensitive nature, manufacturers often do not publish the costs of particular vehicle components, such as the glider, in order to maintain their competitiveness with other companies. As a result, in order to estimate these costs and the overheads in this work, both the vehicle purchase costs (in Table 4) and the cost of individual powertrain components were used in Eq. (1) to derive estimates for these costs. The individual costs of each major powertrain component are given in Table S5 in the supplementary materials and were sourced from [39] as well as equipment manufacturers and were scaled based on vehicle requirements respectively. For BEVs this included the lithium-ion battery and electric motor. FCEVs included the fuel cell, storage tank, battery, and electric motor. For ICEVs, this included the combustion engine and fuel tank. The calculated costs of all vehicle gliders are given in Table S5 in the supplementary materials respectively.

$$\text{Vehicle Purchase Cost} = \text{Glider} + \text{Powertrain} + \text{Overheads} \tag{1}$$

Estimates for overhead costs were taken from [30] and included production (engineering and R&D), sales, and profit. These cost contributors were assigned an individual share of the vehicle manufacture price, with the total overheads equalling 75% of the manufacturing (vehicle) cost respectively.

2.5. Vehicle depreciation

Depreciation is complicated, non-linear, and challenging to estimate as it is influenced by mileage, powertrain, brand perception, vehicle features, and condition, for example [31]. It typically accounts for a large portion of the TCO and is of high interest to fleet owners. It is calculated by subtracting the salvage value from the purchase cost (inclusive of any grants/subsidies) and dividing by the service life.

Several financial models estimate depreciation of up to 40% after the first year, with [32] stating the average new vehicle may lose ~60% of its value after 3 years. For ZEVs, depreciation may vary significantly because these vehicles have not yet reached their end of life, leaving limited historical data.

A residual value (RV) of 50% was set for ICEVs after the first two years of ownership, with the rate slowing towards the maximum ownership of 16 years. After 12 years, depreciation ceases and RV drops to 20% where it remains [33]. found minimal difference in depreciation across powertrains. Consequently, the same rate is applied to BEVs and FCEVs. This depreciation profile is shown in Figure S2.

2.6. Battery and fuel cell replacement and resale value

FCEVs in this study use PEM fuel cells which are the most common for transport applications due to their high energy density, safe operating temperatures, compactness, maturity, and high durability. For BEVs, lithium-ion batteries are used. These are commonplace in BEVs today offering low maintenance, high energy density, and fast charging compared to alternatives [34].

Component replacements are not expected for ICEVs but are for BEVs and FCEVs [35]. report many BEVs offer 10-year warranty for batteries, while for FCs predictions are difficult since historical data is limited. However [36], referenced two reports quoting lifespans of 200 000km and 247 000km. As a result, this model sets a limit of *either* 10 years of service or 200 000km before replacements are needed.

For component disposal [35], suggests spent batteries are unsuitable for a second automotive use, but since they retain ~80% of their capacity, can be re-used outside of transport applications [28]. reported

Table 3. Fleet vehicle fuel consumption and baseline daily mileage.

Vehicle Type:	Car	City Bus	Long Haul Truck	Tipper Truck	Refuse Collection	Forklift
Approx. GVW (t):	1.8	12	44	26	26	12
Payload (t):	-	60 (passengers)	26	12	12	8
Generic Daily Mileage (km):						
All Powertrains	64.4	99.1	496.4	33.2	54.7	29.8
Fuel Consumption (kWh/100km):						
ICEV	65.9	240	194	211	211	694.6
BEV	16	70	100	130	130	212.4
FCEV	18.3	217	343.6	253	645.8	354

Table 4. Purchase costs used in the study.

	Bus	Truck	Tipper	Refuse	Forklift
FCEV	£500 000	£300 000	£150 000	£400 000	£45 000
BEV	£350 000	£400 000	£150 000	£357 000	£40 000
ICEV	£290 000	£250 000	£75 000	£152 500	£30 000

PEM FCs have a 20% recoverable value, whilst [29] said they expect batteries to be repurchased for 30% of their original cost. These resale figures are applied to this study and component salvage value is deducted from the vehicle purchase cost, so the depreciation component of the TCO accounts for these cost savings.

2.7. Vehicle tax

UK vehicle tax includes vehicle excise duty (VED), and a road user levy (RUL) for HDVs. For ICEV LDVs, VED is £155/year whilst for HDVs this depends on vehicle weight, though for most vehicles in this study the cost is £300/year. RUL varies with weight across a wider range, with all figures sourced from UK government and DVLA road tax databases [37]. Since it is unreasonable to predict future tax rates and structures, these are assumed to remain constant over from 2021-2050. All ZEVs are tax-free, confirmed in a TCO report on electric refuse collection vehicles in Manchester City Council fleets [29]. A summary of the tax figures used in the study can be found in Table S7 in the supplementary materials.

2.8. Insurance and maintenance

Many businesses use fleet insurance to cover all vehicles with one fixed annual cost. However, this complicates individual TCO estimation as it is difficult to assign portions of this single fee to each vehicle. Insurance for individual vehicles is also strongly influenced by driver characteristics like age, gender, accident history, and location, as well as vehicle-related factors. To overcome this, estimates for annual insurance of 1.5% of the purchase costs, based on [38] have been used as a guideline.

Maintenance is inclusive of services, MOT, and repairs. Since figures vary on an individual vehicle basis, fleet operators, TCO reports, and direct quotes were used to generate estimates, giving the costs presented in Table S8 in the supplementary materials. All insurance and maintenance costs are assumed to stay constant throughout the 2021–2050 study period respectively.

2.9. Financial incentives and deterrents

Generally, ZEVs have higher purchase costs than ICEVs, so financial incentives are imposed in the early stages to encourage their uptake. Deterrents on ICEVs may also be used to discourage fossil fuel use. Tools used in this work include purchase grants (Figure 2), fossil taxes (Figure 3), and road use charges (Eqs. (2) and (3)). Free parking is another example of ZEV incentivisation (outlined red in Figure 1 shown previously). However, since most TCO analyses exclude this component, and this work focuses on vehicles for fleet use with B2B refuelling in areas where parking is not a concern, this is omitted.

Since BEVs and FCEVs are typically characterised by higher purchase costs than ICEVs, discounts are necessary and effective in the early stages to encourage uptake. Two discount rates (standard and high) are applied to this model to alleviate burdens associated with high upfront costs. Here, the high grant discount is double the standard, which is a maximum of 20% for BEVs and 40% for FCEVs, shown in Figure 2. In 2021 FCEVs are discounted up to 40% whilst BEVs are discounted up to 20% since their market is more developed. Although a date has been set for the end of sale of diesel LDVs, no official date has been set for HDVs, though recent predictions have been made for 2040 [27]. As a result, grants are active from 2021-2040, with FCEVs discounted only 5% in 2040 and BEVs excluded by this point. After this time the purchase prices for vehicles must be paid in full, since the market is assumed well established and the ban on new diesel vehicles is put into place forcing consumers to purchase ZEVs regardless of price. As a result, the purchase grant aims to improve the cost competitiveness of ZEVs in the early years of uptake and benefits are not seen beyond 2040.

A taxation on diesel fuel (in addition to fuel duty) can be applied to the model to assess the impact on the competitiveness of ZEVs. This will drive users away from ICEVs and encourage them to consider a ZEV. Two dynamic fossil tax rates are included in this model and shown in Figure 3: a low rate and high rate (double the low rate). Rates start at 5% and 10% in 2021.

Fuel duty is a tax embedded in the cost of diesel and was approximately 58p/L at the time of this research, bringing in considerable funds to the UK government. In 2019/2020, the total revenue generated was approximately £28.4bn [41]. As the UK transitions towards low carbon transport, this revenue will be lost, so new schemes will be needed to bridge this gap. One solution used in this model is a road use charge where users pay an equivalent tax per km travelled. This is shown in Eqs. (2) and (3) below.

$$\text{Current Fuel Duty Tax} = \frac{£0.58}{\text{L}}$$

$$1\text{L Diesel} = 9.96\ \text{kWh}$$

$$\text{Equivalent Cost} = £0.58\ {/}_{9.96\ \text{kWh}} = £0.0582\Big/\text{kWh} \tag{2}$$

$$\text{Road Use Charge} = £0.0582{/}_{\text{kWh}}\ \text{x Fuel Consumption}\ \text{kWh}{/}_{\text{km}} = £\Big/\text{km} \tag{3}$$

3. Results and discussion

3.1. Breakdown of cost components

Figure 4 shows the cost contributions that each component has on the overall TCO for diesel vehicles under base case conditions and is given as

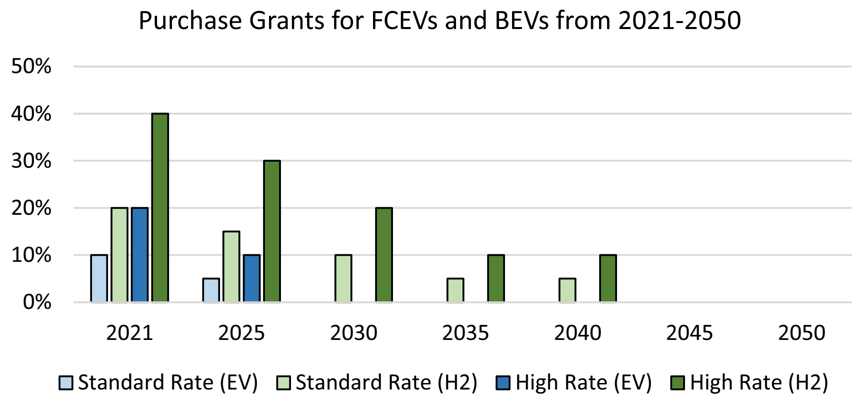

Figure 2. Purchase grants for ZEVs from 2021-2050.

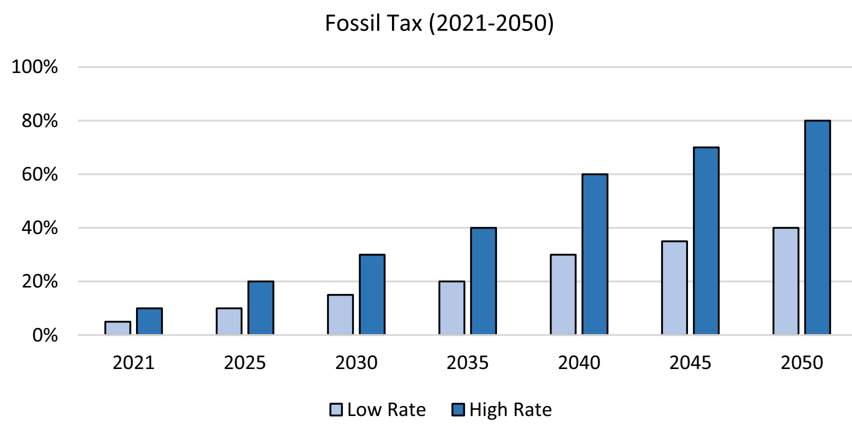

Figure 3. Fossil tax rates from 2021-2050.

an example to facilitate insight, therefore figures for ZEVs are not included. From Figure 4 and for all ZEV scenarios too, for each vehicle and powertrain type, the depreciation, maintenance, tax and insurance, and component replacement costs are fixed with their costs per km the same regardless of the fuel scenario. The fuel cost is the only variable influencing the overall TCO of the vehicles and the subsequent percentage contribution each parameter makes to the total cost per km. From Figure 4, fuel costs make up anywhere between 20% (tipper) and 73% (forklift) of the TCO for diesel vehicles. Although not shown here, for ZEVs, this range is even wider and for this reason, analysis will focus mainly on fuel costs.

For the vast majority of vehicles and fuel scenarios considered in this study, the cost components with the greatest contribution to TCO are fuel and depreciation. For ZEV scenarios, the portion accounted for by depreciation is higher due to their increased purchase costs compared to ICEVs. The impacts of battery and fuel cell component replacement can also be significant for particular vehicle types and shows a variable impact across their TCO. For example, tippers, refuse, and forklift vehicles do not require replacements during their lifetime and therefore have a zero contribution from component replacement in their TCO. However, for cars, buses, and trucks, since they have much higher generic mileage requirements (shown previously in Table 3), battery and fuel cell

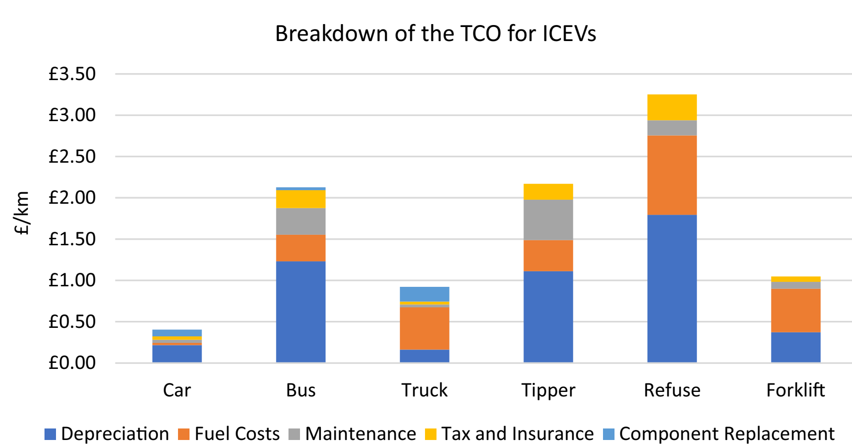

Figure 4. Breakdown of cost components making up TCO of ICEVs.

replacements are necessary in order to maintain operation. The large variation in the contribution of these replacements to TCO was calculated and ranges from 19-21% for FCEV cars whilst for buses this is only 1.5–1.8%. Although both vehicles only have one fuel cell replacement throughout their lifetime, this differential is largely attributed to the fact that passenger cars have a much lower initial purchase price (£60,000 compared to £500,000) and also have a larger fuel cell (114 kW compared to 75 kW), which accounts for a much larger portion of the total lifetime costs. For FCEV long haul trucks, the contribution of fuel cell replacements is also significant and ranges from 15-28%. Although the high mileage demands from trucks allows the costs to be spread out over more use, it means more frequent replacements are required which leads to additional costs.

Maintenance costs are fixed annual costs and have a significant impact on diesel HDVs, particularly for buses which incur the highest costs of £16,000/year and tipper trucks which have both low mileage and sizeable costs of £8,100/year, shown in Table S8. These costs are lower for ZEVs as they benefit from fewer moving parts in their powertrains, so the fraction of the TCO accounted for by maintenance is lower.

3.2. Base case TCO

The differences in baseline TCO between ICEV, BEV, and FCEV for each of the fleet vehicles is given below in Figure 5 as an absolute value in £/km.

The figure shows that for all passenger car fuel scenarios, the TCO remains below £0.50/km. All BEV passenger cars offer cost advantages when compared to FCEVs and are the closest fuels considered to achieving diesel parity. The 225 kW turbine, 50-50 Split, and 100% RES scenarios are only 12–16% more costly than diesel per km in 2021, at £0.339/km, £0.352/km, and £0.339/km despite their higher vehicle purchase costs. Since BEV passenger cars benefit from their electricity being generated locally on-site at the point of use, they avoid additional distribution costs which several hydrogen fuel scenarios incur. As most of the cost parameters are the same for FCEVs and BEVs (i.e. ZEV cars have the same purchase price, annual maintenance, tax and insurance, and component replacement frequency), the fuel cost is the only variable parameter to the TCO. As a result, the electricity price is critical to ensuring ZEV competitiveness. Consequently, the high cost of electricity from rapid chargers (£0.24/kWh) leads to a higher total cost per km. Therefore, cars fuelled using rapid chargers are currently 25% more expensive to run per km compared to diesel and are the most expensive electric fuel option.

For FCEVs, costs must fall if they are to reach parity with other fuels. FCEV passenger cars in all hydrogen scenarios are more expensive than their ICEV equivalent. The most competitive scenario is 100% RES hydrogen, with a TCO of £0.377/km, which is still 25% higher than diesel and equal to the costliest BEV scenario (using rapid chargers). All other hydrogen scenarios give a higher TCO. The second most competitive route is hydrogen from SMR using pipeline distribution, which is still 29% more expensive than the diesel scenario per km. In terms of the costliest FCEV car scenario however, liquefied hydrogen from SMR w/ CCS has a TCO of £0.416/km, 38% higher than diesel. This is largely due to the additional electricity demand associated with the liquefaction process, which is very energy intensive requiring 10 kWh/kg H_2. In addition to this, hydrogen transported using diesel powered tube trailers and liquid tankers incurs additional costs associated with the vehicle/driver OPEX which should be acknowledged. It is evident from these figures that electricity currently offers greater cost advantages in terms of TCO per km in the passenger car sector, partly due to its efficient generation but also because of the absence of conditioning and distribution stages.

For HDVs, ZEV refuse collection vehicles are the most expensive of all vehicles considered in the study with their TCO ranging from a minimum of £2.054/km (BEVs using 100% RES electricity) to a maximum of £3.746/km (FCEVs using 225 kW electrolytic hydrogen). This is because refuse vehicles have one of the highest purchase prices of all vehicles considered, a low daily mileage compared to long haul trucks and buses which reduces the spreading of costs per km, and a very high fuel consumption, especially in the case of FCEVs with 19.4 kg H_2/100km. Furthermore, as insurance is equal to 1.5% of purchase costs, refuse vehicles have one of the highest annual insurance costs. The largest cost component in the ZEV powertrain is the battery or fuel cell which is more expensive for HDVs with greater power demands. For diesel refuse vehicles however, TCO is much lower at only £1.435/km largely because of the cost difference in purchase price. Here, the diesel refuse vehicle costs only £152,500 compared to £357,000 and £400,000 for the BEV and FCEV equivalents.

Focusing on FCEVs, a number of HDVs (buses, trucks, and refuse vehicles) generally have a much higher TCO compared to their BEV equivalents. This is primarily because these vehicles have a high cost difference in their purchase prices (similar to refuse vehicles outlined earlier), which has the greatest impact on overall TCO, since they directly influence annual depreciation and insurance costs. Most FCEVs suffer from high upfront costs as they are currently less mature than BEVs and don't have the same advantages of economies of scale and established supply chains. The difference in purchase cost for BEV and FCEV buses, trucks, and refuse vehicles is approximately £150,000, £100,000, and £43,000 respectively, shown earlier in Table 4. In contrast, since the purchase costs of FCEV and BEV cars, tippers and forklifts are similar, they share a TCO that is more competitive.

Under these 2021 base case conditions, several BEV HDVs are already cost competitive with diesel. For FCEVs however, only forklifts are competitive. BEV buses, trucks, tippers, and forklifts are either below the

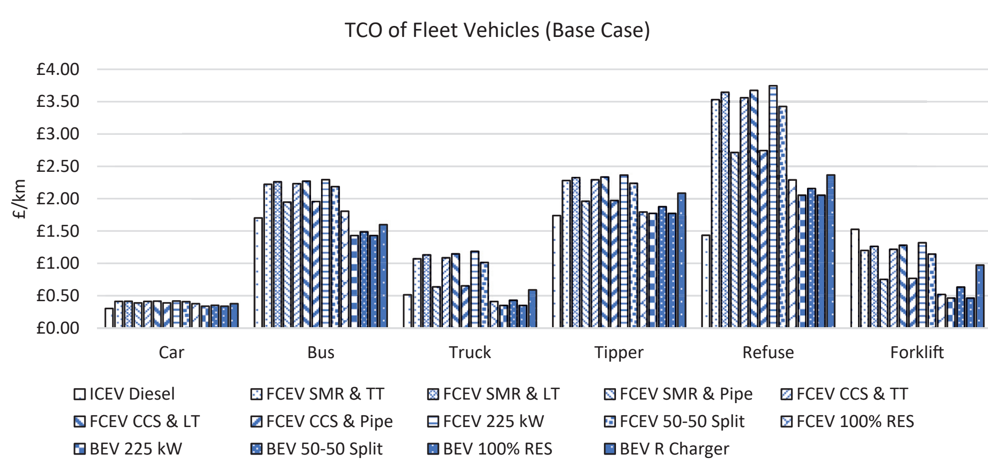

Figure 5. TCO of all vehicles and powertrains in the baseline scenario.[1].

diesel TCO baseline or close to reaching it. In particular, BEV trucks using 225 kW and 100% RES electricity are much cheaper on a per km basis than diesel or hydrogen, both at only £0.349/km. This is because the high mileage requirements and high fuel demands from trucks benefit from low renewable electricity costs. All FCEV forklifts are currently competitive with diesel, whilst buses using hydrogen from 100% RES, SMR w/pipeline, and SMR & CCS w/pipeline are very close to reaching competitiveness being only 6%, 14%, and 15% more expensive per km. This data shows that hydrogen is only competitive with diesel in particular HDV applications and is yet to compete with battery electric since none of the FCEVs TCO fall equal to their BEV equivalent.

[1]SMR: Steam Methane Reforming, CCS: Carbon Capture and Storage, 225 kW: 225 kW Turbine, 50-50 Split: Grid and Renewable Electricity, 100% RES: 100% Renewable Electricity Supply, R Charger: Rapid Charger, TT: Tube Trailer, LT: Liquid Tanker, Pipe: Pipeline.

The effects of various financial incentives and deterrents on ZEV competitiveness are investigated in the next section, along with changes to the vehicle ownership periods and components costs respectively.

3.3. Sensitivity analysis

Several input parameters have been changed to examine their impact on TCO competitiveness. Justifications are given in Table S9 in the supplementary materials. Input parameters are split into two categories: Common parameters (applicable to all powertrains), and fuel-specific parameters. The variance of the TCO from the base case under new parameters was calculated and the new TCO is presented in radar plots to identify the most impactful parameters. The parameters selected for further analysis are given in Table 5. An example of this radar plot for a FCEV bus is given below in Figure 6.

From the radar plot in Figure 6, it is clear that the common parameters of ownership period and maintenance lead to the most significant changes in TCO, whereas other parameters like residual value, powertrain price, and fleet size are less important with only minor impacts on costs per km. For fuel specific parameters, the most impactful parameters were purchase grant, hydrogen fuel price, and battery and fuel cell residual value (Table 5). To understand their effects on the competitiveness of ZEVs, TCO figures under these new conditions were calculated and are discussed further in this section.

All graphical results from the sensitivity analysis are provided in Figures 7, 8, 9, 10, 11, 12, and 13. The figures show the TCO for all vehicles under each fuel and distribution scenario as a percentage of the diesel TCO reference. Due to page limits, discussion will largely focus on FCEVs.

3.3.1. Vehicle ownership period

The ownership period was varied from a minimum of 6 years to a maximum of 16 years which aimed to encompass the average lifetime of a HDV in the UK, which is 12 years [27]. This is shown in Figures 7 and 8. The only components of the TCO influenced by ownership are depreciation and component replacement, since batteries and fuel cells are replaced after 10 years of operation. Fuel costs in the base case analysis are fixed at 2021 prices and it is assumed that maintenance, tax, and insurance costs remain consistent over each year the vehicle is owned. Diesel vehicles benefit from low purchase prices (and depreciation costs) compared to ZEVs, though their higher fuel costs per kWh gradually reduce this advantage over an increasing ownership period.

Table 5. Common and fuel-specific input parameters explored further in the sensitivity analysis.

Common Parameters	Fuel-Specific Parameters (FCEV-Focus)
Vehicle Ownership Period (6 and 16 Years)	Battery and Fuel Cell Residual Value (Equal to 50%)
Maintenance Cost (50% Lower)	Hydrogen Fuel Price (20% Lower)
	Purchase Grant (Standard and High)

For a short service life of 6 years in Figure 7, all ZEV passenger cars have a higher TCO compared to diesel; none of the vehicles are competitive under these conditions. This is partly due to the fact that ZEVs have lower operating costs compared to ICEVs and if they are not used for a time period that is long enough for these benefits to be seen their higher purchase prices will not be offset. The lowest cost hydrogen scenario comes from 100% RES hydrogen at a cost of £0.456/km, compared with only £0.376/km for diesel cars; equivalent to a 21% premium per km. The lowest cost electricity scenario is from both 225 kW and 100% RES at £0.442/km, which is still not yet competitive with diesel roughly 18% higher, though it is still 3% (or £0.014/km) cheaper than the lowest FCEV scenario. As a result of reducing ownership from the 10 year base case to 6 years, the lowest FCEV cost per km increases from £0.377/km to £0.456/km (21%) respectively, whilst for BEVs this rise is even higher at 30%.

Increasing ownership to 16 years in Figure 8 allows the full benefits of the ZEVs low operating costs to be appreciated. As a result, cars utilising 100% RES hydrogen now drop by £0.11/km (29%) to £0.267/km compared to their base case figures and closely approach competitiveness with diesel cars, now only 3% higher per km, down from 25%. FCEV cars using SMR and SMR & CCS hydrogen with pipelines also closely approach parity with diesel, only 7% and 8% more expensive, both at £0.28/km compared to £0.26/km. Despite hydrogen fuel scenarios closely approaching diesel parity for car applications, 3 out of the 4 BEV fuel scenarios surpass diesel TCO; only electricity from rapid chargers remains more expensive (by 9% per km). As a result, electricity remains the lowest cost option for LDV transport under both 6 and 16 year ownership periods.

FCEV trucks running on 100% RES hydrogen, and forklifts running on hydrogen from all fuel scenarios are already competitive with ICEVs under a 6 year ownership period. This improves further with the extension of the ownership period to 16 years where buses utilising 100% RES hydrogen now become competitive, as do tippers running on hydrogen from 100% RES and SMR and SMR & CCS w/pipeline transport. The TCO of all other vehicles and hydrogen fuel scenarios are higher than their ICEV equivalents, though buses and tippers using hydrogen distributed using pipeline are close to approaching it.

Increasing ownership to 16 years from 6 years sees improvement in the competitiveness of some FCEV HDVs against ICEVs. One reason why the TCO of some vehicles remains high compared to diesel (such as trucks and refuse vehicles) and change is relatively small is due to the fact that under this 16 year ownership, fuel cell and battery replacements are now required which incurs additional costs added to the TCO. For larger vehicles with high battery and/or fuel cell requirements, this additional component cost outweighs or counteracts the cost savings over the increased lifetime mileage (due to their lower fuel price compared with diesel).

100% renewable hydrogen gives lowest costs across all HDV types. For buses using this fuel, the total reduction is £1.15/km from 6 to 16 years, and £0.433/km from the 10 year baseline condition (Figure 5) to a 16 year ownership. Hydrogen from SMR and SMR & CCS with pipeline transport remain the next most economical fuel options for FCEVs. Buses and tippers in these fuel scenarios have very similar costs per km to their diesel counterparts after 16 years of ownership. The most expensive FCEV TCO figures are from trucks and refuse vehicles utilising on-site electrolytic hydrogen from a 225 kW turbine at £1.309/km and £4.76/km with a 6 year ownership. After 16 years these costs fall to £1.117/km and £3.137/km respectively; equivalent to a 15% and 34% reduction.

3.3.2. Purchase grant

The high purchase grant applied to the TCO was shown previously in Figure 2 and applies only to ZEV powertrains purely as a financial incentive to reduce the high upfront costs and encourage users to switch to low carbon transport modes. In the 2021 base year, this grant discount is 20% for BEVs and 40% for FCEVs respectively. ICEVs are not subject to discounts since they are a mature technology and likely to be phased out

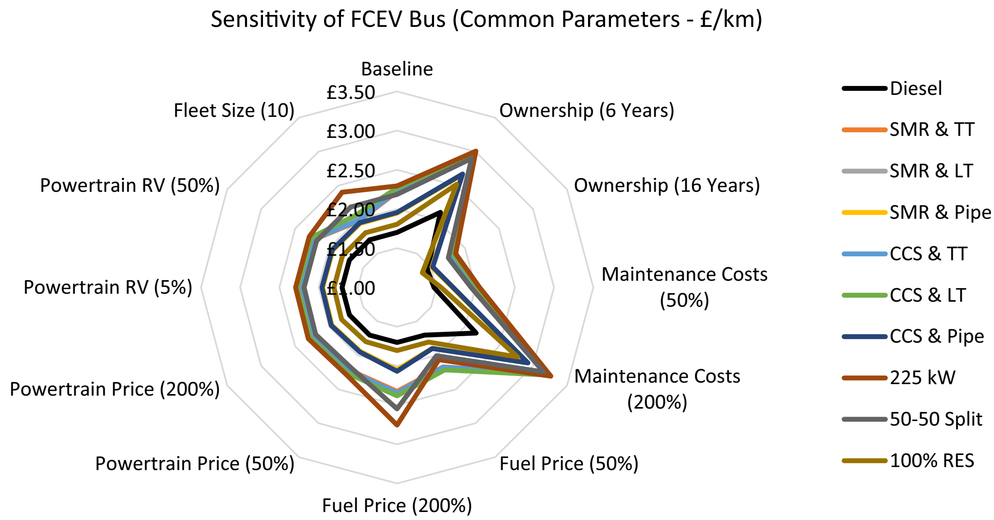

Figure 6. Sensitivity of a FCEV bus TCO to changes in common parameters (in £/km).

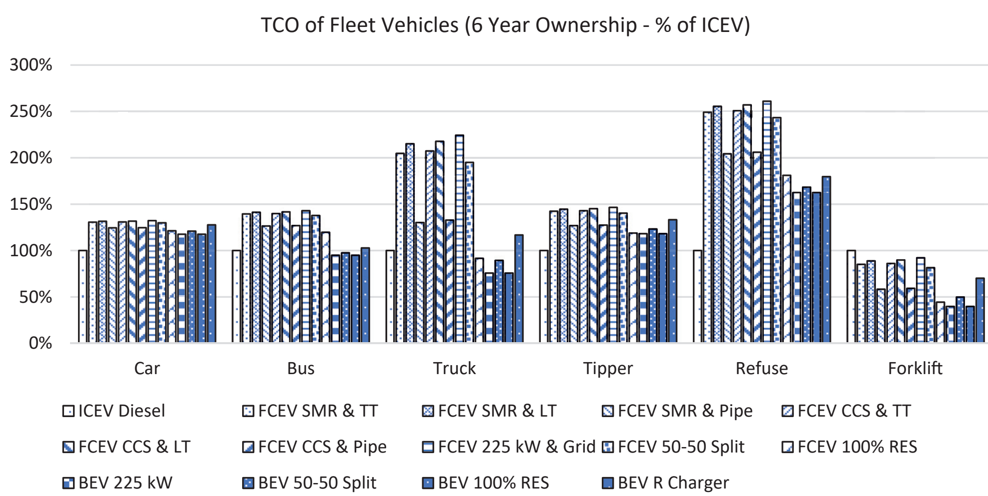

Figure 7. TCO of fleet vehicles under a 6-year ownership period.

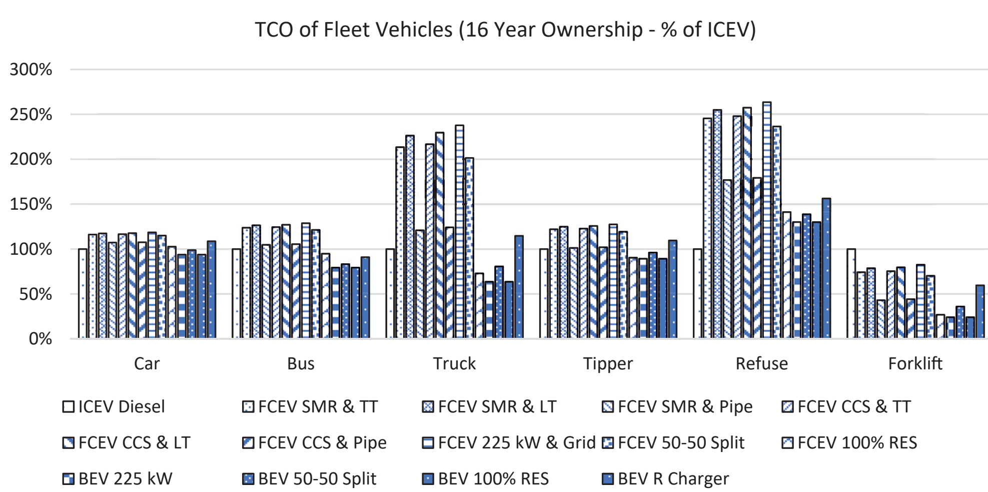

Figure 8. TCO of fleet vehicles under a 16-year ownership period.

from 2030 when the governments diesel ban comes in effect. Although no official date has been set, it has also been predicted that this diesel ban will extend to HDVs by 2040.

After the addition of a high purchase grant, Figure 10 shows that for the majority of FCEVs, the TCO is now roughly equal to or below ICEVs regardless of the fuel scenario used. The only vehicles which have a TCO

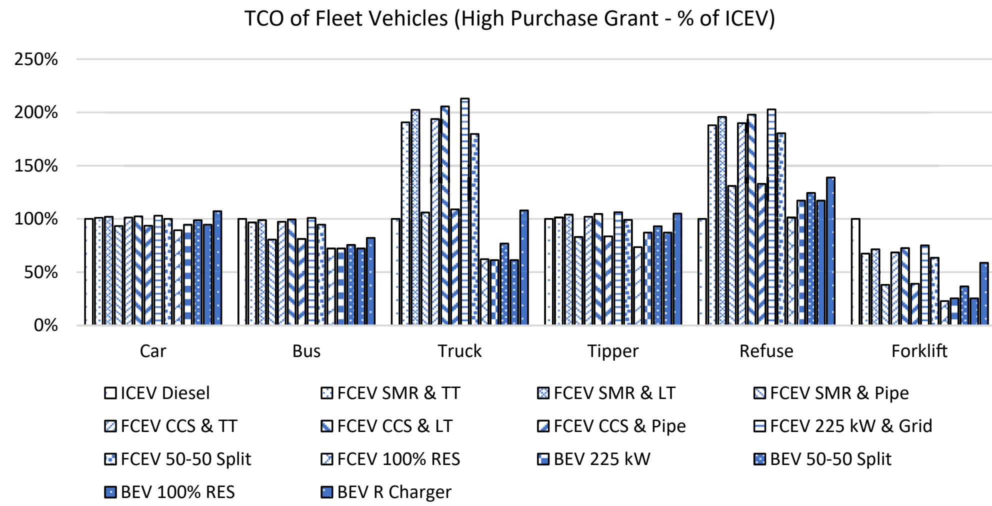

Figure 9. TCO of fleet vehicles under a high purchase grant.

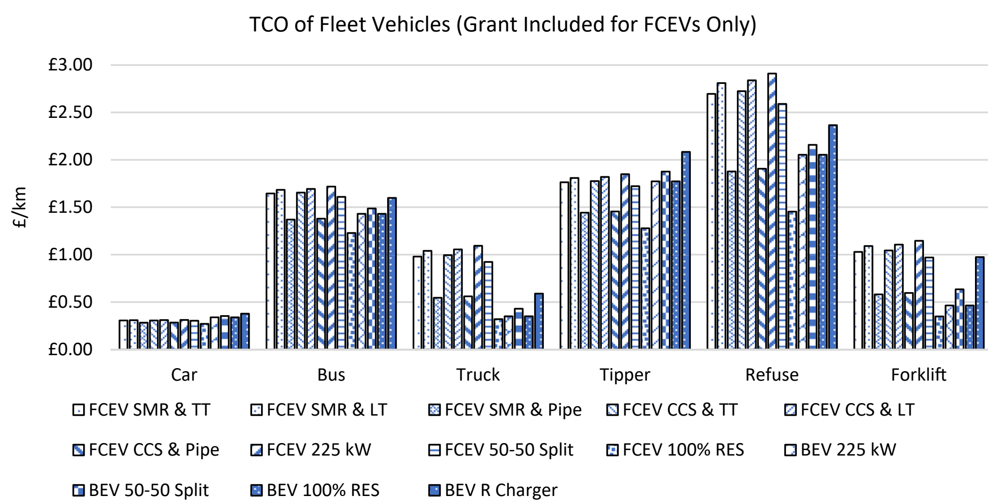

Figure 10. TCO of fleet vehicles with grant included for FCEVs only.

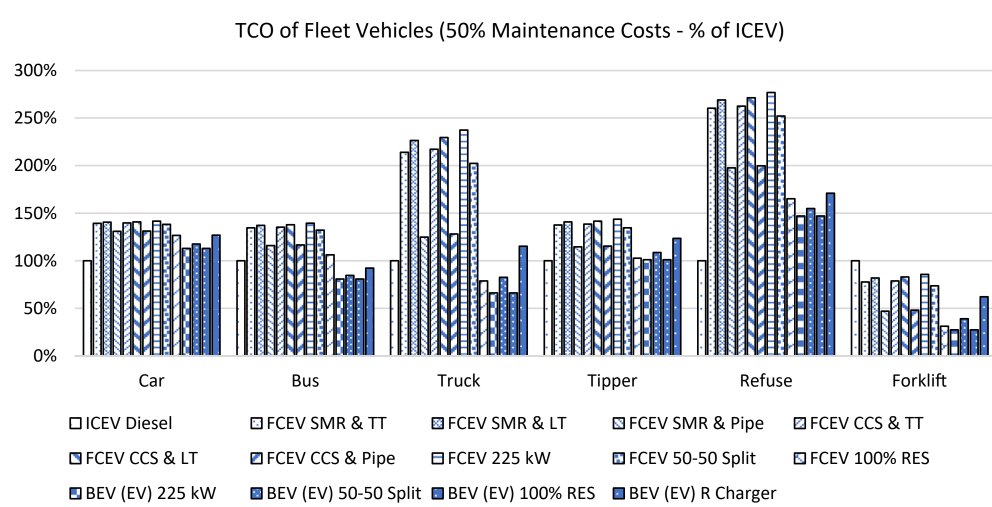

Figure 11. TCO of fleet vehicles under a 50% lower maintenance cost.

higher are trucks and refuse vehicles. However, if hydrogen from SMR or SMR & CCS with pipeline transport is used the TCO of trucks is only 6% and 9% higher per km. The impact of this discount on costs per km is greater for FCEVs since the discount is double that of BEVs, but also because FCEVs generally have higher upfront costs so see a larger absolute saving. The reason for this higher FCEV discount is because their

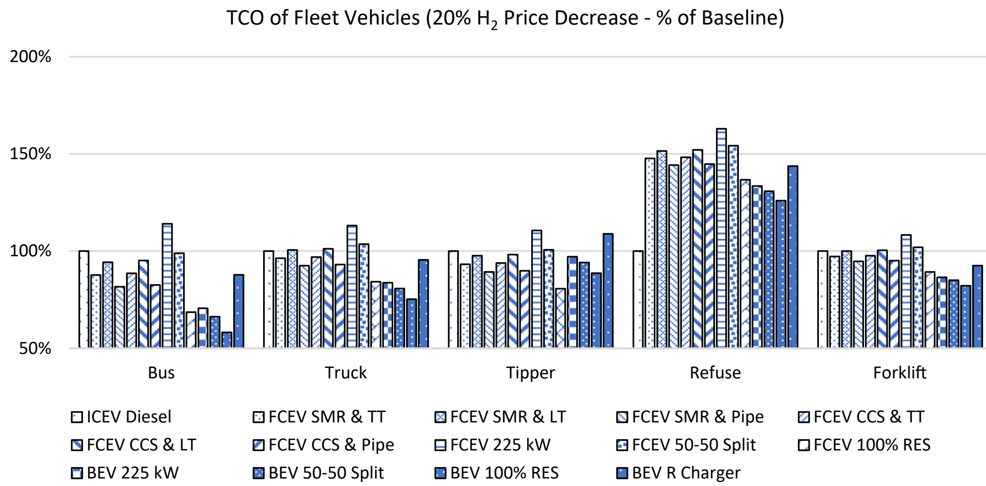

Figure 12. TCO of all fleet vehicles when subject to a 20% reduction in hydrogen price.

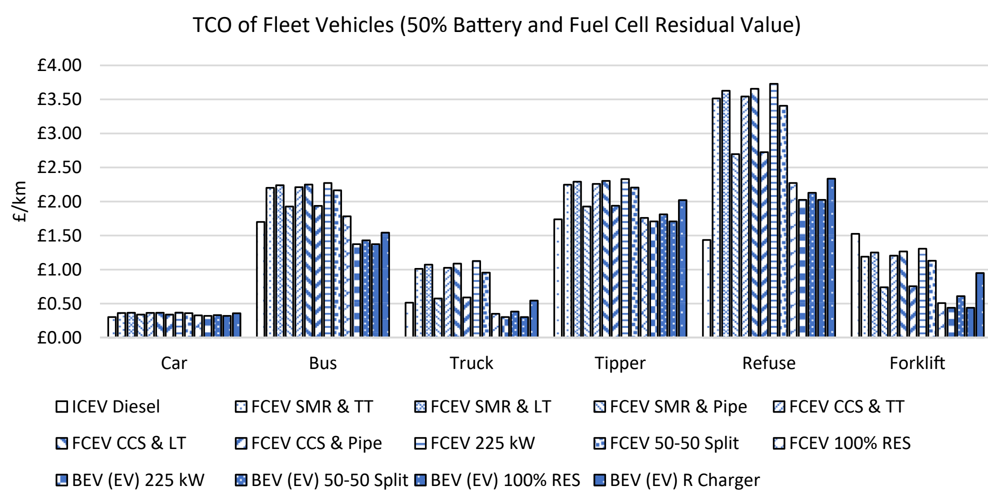

Figure 13. TCO of all fleet vehicles with a 50% battery and/or fuel cell residual value.

market is not yet developed and uptake remains very low. BEVs are becoming much more common in transport and are popular choices for new purchases, so do not need high discounts. It should also be made clear that the insurance costs for vehicles at 1.5% of the purchase cost is calculated using the purchase price prior to any discount applied. This is because insurance costs are independent of government incentives.

For all vehicles except trucks, the lowest TCO across all fuel scenarios comes from 100% RES hydrogen. The fuel scenario which gives trucks the lowest TCO, and the majority of other vehicles their second lowest TCO is BEVs utilising 100% RES electricity respectively. Only cars and tippers have three different hydrogen fuel scenarios which offer a TCO lower than electricity (100% RES, SMR and SMR & CCS with pipeline). Trucks and refuse vehicles utilising hydrogen distributed using tube trailers or liquid tankers as well as electrolytic grid hydrogen are still far from competitive with diesel or electricity because of their high fuel costs per kg which are amplified by the high mileage characteristics of trucks and the high fuel consumption of refuse vehicles. In terms of the lowest cost HDV FCEV, this comes from trucks operating on 100% RES hydrogen at only £0.411/km, dropping to £0.319/km with the grant, making it the third lowest truck TCO of any fuel in the study, now significantly more competitive than the diesel scenario and on a similar level to BEVs. However, these FCEV trucks do not suffer any impacts like BEVs due to their batteries, which are expected to restrict their payload capacity and productivity because of refuelling times, which should be consideration outside of TCO analysis.

Since the TCO of several FCEVs are competitive with BEVs after addition of this grant, if it was only applied to FCEVs, many of the BEVs in the study would lose their competitive edge and it would create a much more attractive business case for hydrogen as a low carbon transport fuel for HDV use. Figure 10 now shows the TCO of fleet vehicles with only the FCEVs in receipt of the high purchase grant. In this case, the lowest TCOs for each vehicle arise from FCEVs, not BEVs.

3.3.3. Maintenance costs

In the early stages of uptake where only a small number of FCEVs are available on the market and where specialised ZEV mechanics are limited, the issues surrounding their operation are not as well understood as ICEVs and therefore more maintenance is expected. However, these maintenance costs are likely to fall in the future due to the increasing number of ZEVs on the road which leads to a greater knowledge and understanding of their operation, meaning the issues can be prevented sooner. As a result, an annual maintenance cost equal to 50% of the base case figure for each vehicle is implemented to identify this impact on the TCO, shown in Figure 11.

The annual maintenance costs used in the base case scenario are highest for ICEV buses and trucks at £16,000/year and £8,700/year, whilst all costs are 30% lower for their ZEV equivalents due to a lower number of moving parts. As a result, the impact of reducing annual costs by 50% is seen more clearly by ICEVs which benefit from a larger saving on a per km basis, since all vehicle types carry out the same mileage regardless of powertrain and all other parameters remain unchanged. Because of this, the TCO of ICEVs falls further per km compared to ZEVs, so the cost competitiveness of ZEVs is worsened. This can be seen in Figure 11 as the difference between the TCO of ZEVs and ICEVs across each vehicle type increases after the reduction in maintenance cost. For example, in the case of buses which have the highest maintenance costs, across all the FCEV buses in the base case (9 fuel scenarios), the TCO ranged from 6-35% higher per km compared to ICEV buses, with none of the FCEV buses cost competitive with diesel. However, after this maintenance cost drop, the range now increases from 6-40% respectively, worsening their competitiveness.

3.3.4. Fuel price

As shown earlier in the example of ICEVs in Figure 4, fuel cost is the only variable influencing vehicle TCO and the subsequent percentage contribution each parameter makes to the total cost per km. The total variation in fuel costs in £/km across all vehicle types and for each of the 3 powertrains under base case conditions is given in Figure S3 respectively. This box plot shows in the case of FCEVs, fuel costs range from a minimum of £0.01/km to a maximum of £1.45/km which is a much wider variation compared to electric fuel scenarios and diesel. This is because the hydrogen fuel can be produced and delivered in more ways, each with a different cost depending on the distribution route and its conditioning. For example, hydrogen transported using diesel powered tube trailers and liquid tankers incurs additional costs associated with the driver salary and vehicle OPEX, something that pipeline transport and electrolysis scenarios avoid. In general, electricity is the cheapest fuel with a maximum of only £0.51/km whilst for diesel this value is £1.12/km. Since fuel costs are one of the largest contributors to the TCO, these figures are very influential to the cost competitiveness of ZEVs and especially FCEV technology. The higher the fuel cost, the greater its contribution is to the vehicles total cost per km.

Figures S4 and S5 support the previous statements further and show the variation in the percentage contribution fuel costs have to the overall TCO for zero emission vehicles. For FCEVs, long haul trucks show the highest max contribution at 65% of the TCO, whilst cars have the lowest max contribution of only ~10%. This gives the total range that fuel cost can contribute towards the TCO for FCEVs. For BEVs in Figure S5, this range is much narrower for several of the vehicles, though BEV forklifts and trucks have the largest maximum contribution of 53% and 41%, compared to the minimum value of 0% in the case of excess renewable electricity.

The price of hydrogen is expected to fall in the future due to improvements in electrolyser efficiency and scale up of production as a result of an increased demand due to a growing FCEVs market. In addition to this, the cost of green hydrogen from renewables has more recently been predicted to fall below grey or blue hydrogen due to recent conflict in Ukraine where natural gas prices have soared due to a lack of supply [44]. To reflect these changes, a hydrogen cost 20% lower than the base case scenario is assumed. Since this has no bearing on ICEVs and BEVs, vehicle TCO using these fuels remain unchanged. The impact of this reduction is that all FCEV buses, trucks, tippers, and forklifts running on hydrogen from any fuel scenario (except for 225 kW electrolytic hydrogen) have a TCO equal to or lower than diesel (Figure 12). However, this 20% fuel price reduction is still not enough to bring all FCEV costs below BEVs, which still remain the cheapest powertrains for all vehicles. Only electricity from rapid chargers remains higher than several hydrogen scenarios.

3.3.5. Battery and fuel cell residual value

Once a battery or fuel cell has reached its end of life in a vehicle, it must be replaced to maintain high efficiency operation. However, these components still retain a significant portion of their original capacity [36]. suggest that lithium-ion batteries are capable of retaining approximately 80% of their original capacity after 10 years of operation, which could be used in other applications outside of transport. Spent fuel cells taken out of vehicles can also be used for backup power applications, replacing conventional diesel generators which are more polluting. Since these components still hold value in other areas, many batteries and fuel cells are resold after use in vehicles rather than being disposed or recycled. In this work a baseline residual value for batteries and fuel cells of 20% and 30% was used, which is in line with current estimates from [29]. The sensitivity analysis considers a maximum value of 50% since these second-hand components are likely to increase in value in the future as uptake increases. The results of a high RV on the TCO for ZEVs are given in Figure 13 below.

Since ICEVs do not have batteries or fuel cells, their results remain unchanged from the base case. However for ZEVs, this residual value of 50% leads to lower depreciation over the vehicle life and therefore reduced costs overall per km since a larger resale amount is deducted from the initial purchase cost. For example, buses and trucks requiring large batteries and fuel cells to provide for their longer duty cycle requirements will retain a larger cost when resold compared to smaller vehicles with smaller powertrain requirements. However, the impact of this increased RV has a very minor influence on FCEV competitiveness. For example, buses running on hydrogen from SMR with TT with a 50% fuel cell RV have a cost of £2.201/km compared to their base case of £2.222/km, which is a decrease of only £0.02/km (~1%). For a FCEV bus, the highest TCO is £2.273/km from a 225kW turbine and the lowest TCO is only £1.784/km with 100% RES. For BEV buses the TCO is lower, with the minimum and maximum ranging from £1.374/km using 100% RES to £1.542/km with rapid chargers.

3.4. Future outlook – TCO from 2021-2050

To complement the analysis of the base case results in 2021, this future outlook examines TCO changes from 2022 to 2050 due to time-sensitive parameters. This offers insight into what year FCEV and BEV TCO intersect ICEVs and become more favourable in costs per km.

3.4.1. Future base case

This section showcases the TCO for each vehicle and fuel scenario with no added incentives or deterrents (the "future base case"), with results provided in Figures 14 and 15 respectively. To limit the size of this section, these figures showcase results for only buses and trucks. This is because these HDVs are the two most common with FCEV versions already in use in many fleets and others in development. After these future base case TCO results, model conditions are changed, and two rates of diesel tax and purchase grants are applied to assess their impact on the TCO of FCEVs. As highlighted previously, the parameter with the largest impact on TCO for all vehicles is fuel cost. Since this work targets the suitability of hydrogen for HDV applications, the future TCO analysis will focus strongly on these fuel costs. In the future base case outlook, fossil tax is not applied and because combustion technology is mature, fuel consumption for ICEVs is assumed to remain constant (see Table S1). As a result, TCO for diesel vehicles remains unchanged throughout this period and analysis focuses on ZEVs.

The variation in TCO for a bus from 2021 to 2050 is shown in Figure 14 and is very minor across the vast majority of fuel types. The only noticeable changes in TCO over this time period are seen by buses which use fuels that are highly dependent on grid electricity. These include electrolytic hydrogen (225 kW and 50-50 split), as well as BEV buses with rapid chargers. Since the diesel TCO remains constant at £1.70/km, ZEV fuel scenarios have the opportunity to intersect it over this period and become cost competitive. However, none of the fuel scenarios reduce the TCO of the bus enough to achieve this. Although diesel TCO is not intersected, buses running on hydrogen from SMR, and SMR & CCS using TT show a very gradually lowering TCO from 2021-2050 and intersect the TCO of buses using 50-50 split hydrogen in this time. In 2021, the TCO of FCEV buses running on SMR w/TT hydrogen is £2.23/km and falls to £2.18/km by 2050. Here, this FCEV bus scenario becomes more cost competitive than 50-50 split hydrogen in 2040.

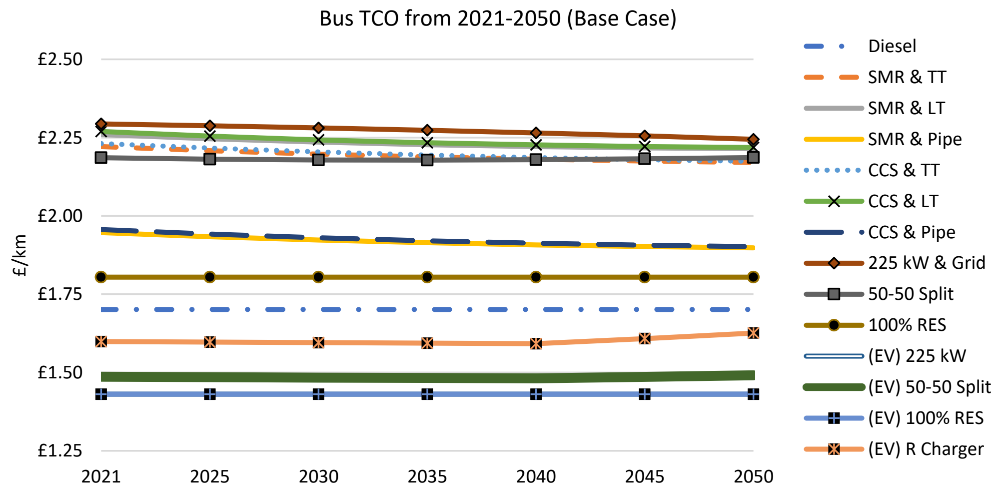

Figure 14. Bus TCO from 2021-2050 under base case conditions.

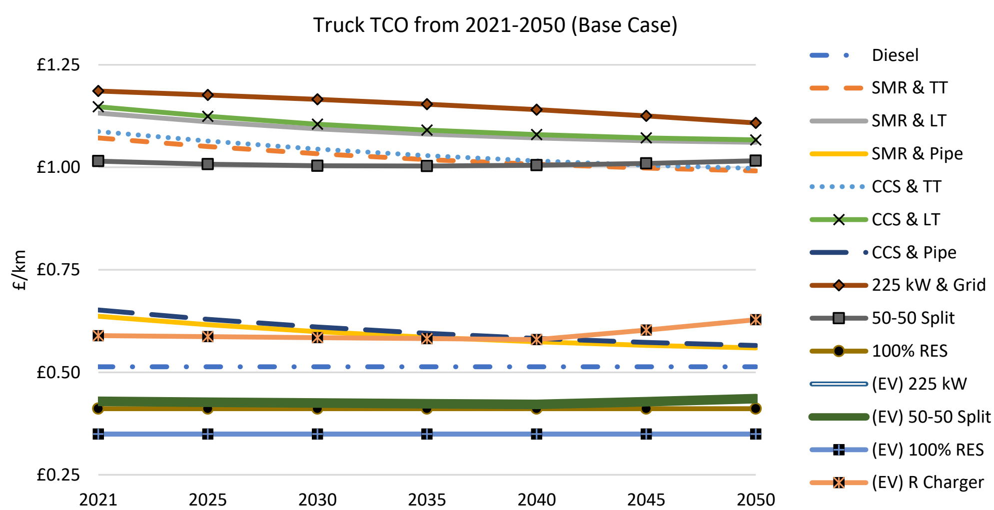

Figure 15. Truck TCO from 2021-2050 under base case conditions.

For FCEV buses utilising electrolytic hydrogen from a 225 kW turbine, and non-electrolytic hydrogen from CCS w/LT, the TCO is the highest in 2050 at £2.25/km and £2.22/km respectively. The TCO in the LT scenarios takes longer to fall because they incur a higher number of costs, such as vehicle OPEX and driver salary which give it a higher cost per kg compared to electrolytic hydrogen. Liquefied hydrogen also has a high grid electricity demand and since grid electricity increases over time from £0.144/kWh in 2021 to £0.255/kWh in 2050, contributes to these higher costs per km. In the case of electrolytic hydrogen, because of rising grid electricity costs and very slow changes to the electrolyser efficiency over time, TCO remains fairly consistent over the time period. In addition to the electrolyser efficiency, costs also fall slightly because hydrogen does not require transport and distribution steps which increase the electricity consumption due to conditioning stages such as compression, for example.

All BEV buses show a lower TCO per km than ICEV and FCEV buses from 2021 to 2050. The TCO of 100% RES, 50-50 split, and 225 kW electricity scenarios remains very similar across the 30-year period, with only electricity from rapid chargers showing a TCO that increases from £1.60/km in 2021 to £1.63/km in 2050, where it closes in on ICEV TCO. This rise after 2040 is attributed to not only the consistent rising cost of rapid charger electricity from £0.24/kWh in 2021 to £0.43/kWh in 2050, but also the effect of energy consumption changes for BEVs over the time period, with efficiency improvements ceasing after 2040. The electricity from these rapid chargers comes at a premium for its convenience and is more expensive than grid electricity at only £0.24/kWh in 2021. Since many BEV bus scenarios (such as 100% RES and 50-50 split) do not change significantly across the 2021–2050 period, this suggests that battery price has a little impact on the TCO, despite prices falling ~£65/kWh over the 30-year period. This supports the earlier statement that ZEV TCO is most greatly impacted by fuel price.

Similar to buses, the base case future outlook for long haul trucks shown in Figure 15. Most fuel scenarios here follow the same order and pattern as Figure 14 except costs per km are significantly lower, partly due to a reduction in fuel consumption for ZEV trucks and a much greater mileage demand of 496 km/day compared to only 99 km/day. In this case, BEV scenarios generally remain the lowest in cost per km with 3 out of 4 fuel scenarios well below the diesel TCO and much more competitive than FCEVs, peaking in 2050 at only £0.44/km. However for BEV trucks using rapid chargers, in 2021 the TCO is higher than diesel at £0.59/km compared to £0.51/km, and similarly to BEV buses, the TCO increases steadily over time due to the change in electricity price to a peak of £0.63/km. During this rise, in 2040 FCEV trucks utilising SMR w/pipe and CCS w/pipe hydrogen intersect and become cost competitive per km. No hydrogen fuel scenarios were competitive with BEVs in bus applications, so this highlights a more economical use of hydrogen in transport.

Results suggest that compared to buses, hydrogen is more competitive for use in heavy duty trucks since a higher number of the fuel scenarios

(3) show a lower TCO than electricity (from rapid chargers) by 2050. The only hydrogen scenario that can compete with diesel and renewable electricity is 100% RES, which remains consistent at £0.41/km. The diesel truck TCO is fixed at £0.51/km whilst BEVs utilising 225 kW and 50-50 split electricity are also more expensive per km than 100% RES. Hydrogen is economically better suited for use in trucks than buses under the conditions of this study since more hydrogen fuel scenarios reach competitiveness with electricity and diesel by 2050.

3.4.2. Future outlook – fossil tax added

The impact on increasing FCEV competitiveness by applying a fossil tax on diesel is examined in this section. The future base case from 2021-2050 now includes an added tax on diesel fuel. The two tax rate profiles were shown previously in Figure 3 and start at 5% (low rate) and 10% (high rate) in 2021, rising to a maximum of 40% and 80% by 2050. TCO results for a bus and a truck now with the inclusion of this tax are given in Figures 16, 17, 18, and 19.

Since the fossil tax applied is only applicable to diesel, a significant change in the TCO of ICEVs is seen, but for ZEVs the TCO remains the same as the future base case in Figures 14 and 15. Unlike the future base case where ICEV costs per km remained constant, now for ICEV buses the TCO increases from £1.72/km in 2021 to £1.86/km in 2050, surpassing one other fuel (100% RES hydrogen) in terms of TCO per km by 2050. The BEV bus fuel scenarios that have a lower TCO than diesel in 2050 are 100% RES, 50-50 split, 225 kW and rapid chargers, whilst for FCEV buses, the only fuel scenario cheaper than diesel is 100% RES hydrogen. Figure 14 showed the FCEV bus TCO using 100% RES hydrogen did not become cost competitive with diesel by 2050, peaking at £1.80/km in 2050 compared to £1.70/km for diesel. However, due to this fossil tax this hydrogen fuel scenario now reaches cost parity in 2038, making hydrogen from 100% RES a more economical option for use in these HDVs. The effect of a small fossil tax brings the time at which this hydrogen scenario is competitive closer by more than 12 years. However, this is only true for the 100% RES hydrogen scenario since no other FCEV buses reach parity with diesel under these conditions. These results suggest that if a government deterrent like this was introduced, the severity of the tax should be increased further if more hydrogen fuels are to be cost competitive with diesel and electricity.

Results are amplified using a high fossil tax as now the diesel bus TCO reaches a peak of £2.01/km in 2050 (Figure 17); an increase of ~18% from the future base case. Similar to the low fossil tax rate, the year at which electrolytic hydrogen from 100% RES becomes competitive with diesel is even sooner now in 2027 respectively. The impact of increasing the fossil tax from the low rate (40%) to the high rate (80%) has accelerated the time at which diesel parity is seen by over 10 years. In the low rate scenario, this 100% RES hydrogen was the only hydrogen scenario that achieved diesel parity before 2050. However, under the higher rate, hydrogen from both SMR and SMR & CCS w/pipeline transport now intersects and becomes cheaper per km in 2037. Purchasing an ICEV bus in 2021 with a high fossil tax is more costly per km than 4 of the 13 ZEV fuels, but after 2037 it would be costlier than 7 fuels respectively.

TCO for trucks under low and high fossil tax conditions from 2021-2050 are shown in Figures 18 and 19. Results follow a similar pattern to buses, with all ZEV truck scenarios having a TCO equal to that of the future base case (Figure 15). In Figure 18, hydrogen from SMR and SMR & CCS transported using pipeline reaches parity with diesel in 2037 at £0.59/km. In the future base case, these ZEV fuels never reached parity with diesel which means the low tax was the difference between FCEV trucks being financially advantageous over ICEVs. Truck TCO using electricity from rapid chargers still remained more costly per km over the 2021–2050 period despite the diesel tax, though all 3 remaining electricity fuel scenarios had the lowest truck TCO recorded, reaching a peak of only £0.443/km in 2050. After a high fossil tax is added, 6 of the 13 ZEV fuels showed a TCO below diesel and BEV trucks using rapid chargers now became the same price per km as diesel in 2050 at £0.65/km. FCEV trucks using hydrogen from SMR and SMR & CCS w/pipeline reach diesel parity 7 years faster than the low tax, now in 2029. The impact of increasing the tax did not lead to a higher number of hydrogen fuel scenarios achieving parity however, with still only 3 of the 9 fuels below diesel per km by 2050.

3.4.3. Future outlook – purchase grant added

In this section the future base case TCO across the 2021–2050 period now includes a purchase grant on ZEVs to reduce their high upfront costs and incentivise their uptake. The two rate profiles (standard and high) for ZEVs were given in Figure 2 and vary in discount depending on the powertrain type (i.e. BEV or FCEV). In 2021 FCEVs are discounted up to 40% whilst BEVs are discounted up to a maximum of 20% since their market is more developed. Although a date has been set for the end of sale for new diesel cars and vans, no official date has been set for HDVs, though several projections have been made for 2040 [27]. As a result, grants are active from 2021-2040, with FCEVs discounted only 5% in 2040 whilst BEVs are excluded from grants by this point. After 2040 the purchase prices for vehicles must be paid in full, since the market is assumed well established by this point and the ban on new diesel vehicles now forces consumers to purchase ZEVs regardless of their price. As a result, the purchase grant improves the cost competitiveness of ZEVs in the earlier years of uptake only and its benefits are not seen after 2040. By 2040, vehicle purchase costs rise from the previously discounted cost to their base case values for that year, shown by an increase in TCO after 2040 in the following graphs. The TCO results for a bus and a truck are given in Figures 20, 21, 22, and 23.

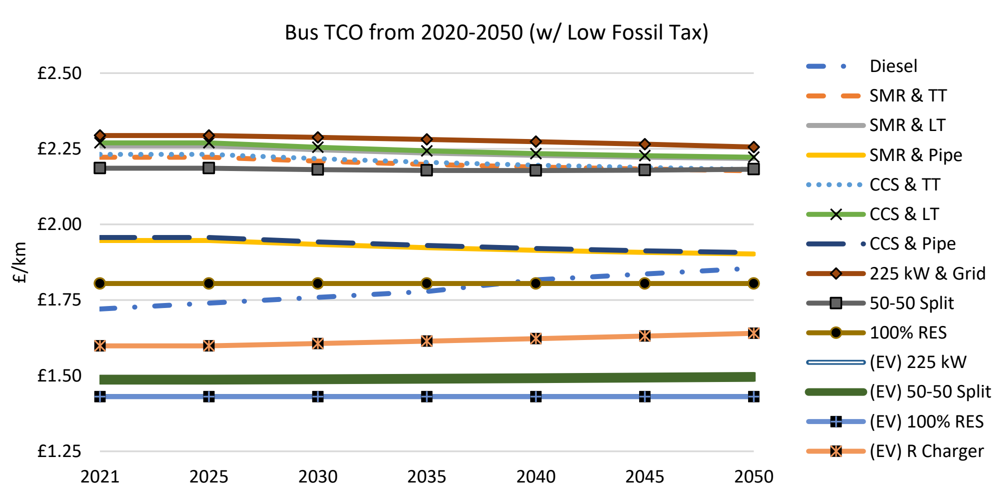

Figure 16. Bus TCO from 2021-2050 with a low fossil tax added.

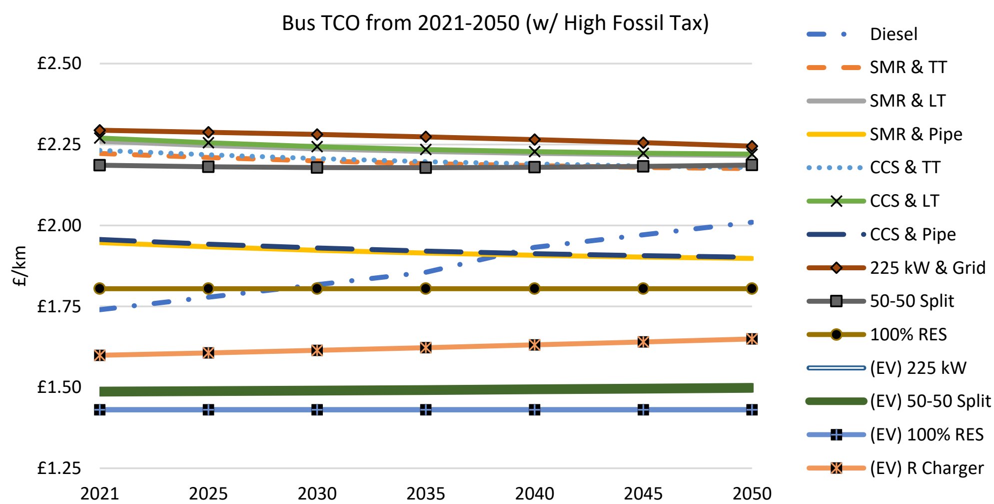

Figure 17. Bus TCO from 2021-2050 with a high fossil tax added.

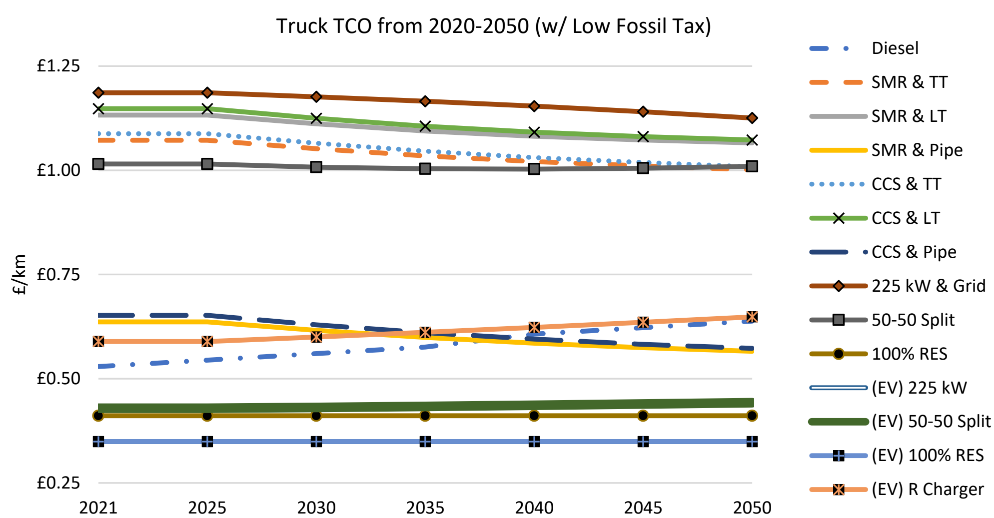

Figure 18. Truck TCO from 2021-2050 with a low fossil tax added.

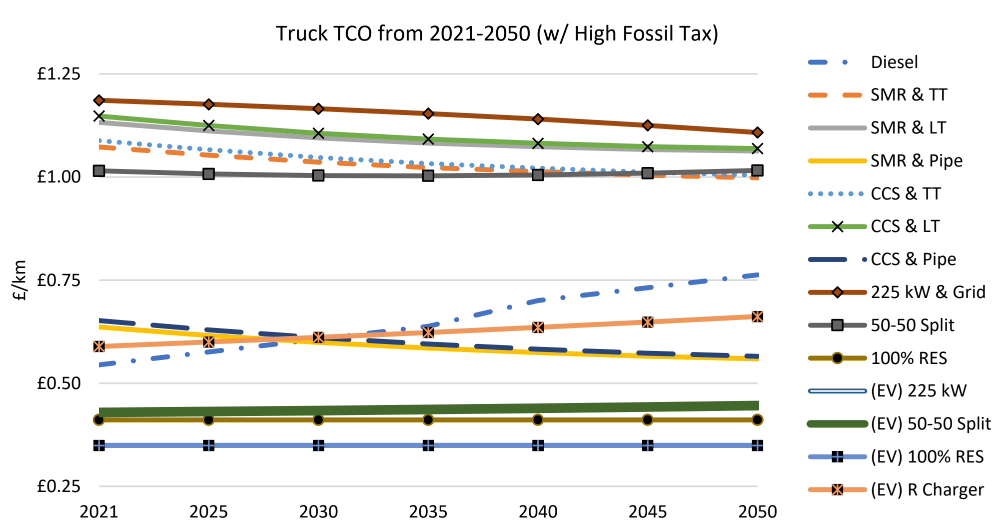

Figure 19. Truck TCO from 2021-2050 with a high fossil tax added.

Figures 20 and 21 show the TCO profiles for a bus and a truck under standard purchase grants. Since this only applies to ZEVs, the ICEV bus and truck TCO remains fixed at £1.70/km and £0.51/km; the same as the future base case in Figures 14 and 15.

For ZEVs, the influence of this purchase grant on TCO is quite low. For BEV buses and trucks operating on electricity from rapid chargers, the TCO in 2021 (when the grant is highest) is £1.50/km and £0.57/km, compared to their future base case values in 2021 of £1.60/km and £0.59/km respectively. This is only a reduction in cost per km of ~6% and ~4%. As the purchase grant for BEVs is only applied from 2021 to 2025, the TCO in 2030 onwards falls back to this more consistent future base case level with no discounts applied. For other BEV bus and truck scenarios, the effect of this purchase grant is even smaller and has a negligible impact on competitiveness. The impact of the discount is that it helps ZEVs achieve parity with diesel in the early stages to increase their attractiveness to consumers and fleet operators. Over time, these benefits are lost as ZEVs become the dominant powertrains in transport. For example, in the future base case for FCEV buses, those running on SMR and SMR & CCS w/pipeline hydrogen are more costly per km than diesel in 2021, with their TCO both at £1.95/km compared to £1.70/km for ICEV buses. However, after the inclusion of the standard purchase grant, their TCO in the year 2021 now falls just below that of diesel, achieving cost parity. This creates a better business case for FCEV buses operating on these fuels and encourages uptake in the earlier stages.

Comparing FCEV bus and truck TCO in 2021 (with the grant applied) to their future base case values shows similar results to BEVs. In the 225 kW electrolytic hydrogen scenario, bus and truck TCO is £2.29/km and £1.19/km in 2021 which falls to £2.00/km and £1.14/km with the application of the grant. This is a slightly higher reduction at 13% and 5% compared to BEVs but since the grant was double, the influence on TCO is still low. Figure 20 clearly shows the difference in TCO between the base case and under these standard grant conditions falls slowly from its maximum in 2021 (when the grant is highest) to 2035 for the hydrogen scenarios, and then the rate of this decrease in cost per km slows thereafter before eventually being removed.

Whilst the grant is active, it also alters the competitiveness of the fuels, as the TCO of some hydrogen scenarios falls below diesel in the early years. This is important because the sale of diesel cars and vans is going to be banned within the next decade and after 2030 consumers will have no choice but to purchase ZEVs. However, from now until then if a purchase grant like this one is a key difference between people choosing to use diesel and using hydrogen fuels, and if it will encourage people to purchase ZEVs earlier and accelerate carbon savings and the transition to more sustainable transport, it should be considered. This tool shows effectiveness for lowering the TCO closer to or below ICEVs in the early stages of ZEV uptake.

If the grant is increased further, the effect on bus and truck TCO is shown in Figures 22 and 23. As the discount for FCEVs falls from its highest point in 2021 (40%) to its lowest point in 2040 (5%), for several hydrogen scenarios it leads to an increase in TCO compared to the previous (discounted) year, but a lower TCO than the future base case for that year. For example, in 2021 for FCEVs the purchase grant is 40% but in 2025 it falls to 30%. Since this discount is lower in 2025 it leads to a higher cost per km compared to the 2021 cost as the depreciation component of the TCO increases per km, and so on. This response increases after each reduction in discount until 2040 when the TCO matches its future base case value without discounts. This explains the slow change in cost thereafter due to time-sensitive inputs which were covered in the future base case. This increase in TCO after each reduction in grant discount is seen clearly in the hydrogen scenarios in Figures 22 and 23, such as SMR w/pipeline, showing a steep rise in TCO between 2021-2030 as the severity of the grant falls. The reason for the decline in TCO between 2035 and 2040 is due to the purchase grant used over time. From 2021 to 2035, the grant decreases 10% every 5 year period, but in 2035 and 2040, the grant remains the same at 10% which is its lowest value in the high grant scenario. As a result of this stagnation, the TCO falls and closely approaches its future base case value.

After addition of a high purchase grant, 10 of the 13 ZEV buses are already below the ICEV TCO in 2021. For trucks which have a lower purchase price however, this number is lower and no new hydrogen fuels become cheaper than diesel in 2021, though some closely approach it. This makes the economics of owning and operating a ZEV much more attractive in the early stages of uptake as this is typically when their costs are highest and ICEVs have an advantage from their more developed market.

4. Limitations and Recommendations

Despite the high level of detail in both the modelling and analysis of this work, no work can cover all aspects thoroughly and so there remains a number of improvements which could be made to increase its quality further. Some of these are bulleted below. Note that this list is not exhaustive.

- Vehicle Fuel/Energy Consumption: Due to limited market availability, fuel consumption data for some ZEVs was estimated and therefore may not be an accurate representation of actual figures. These figures should be updated as new vehicles are brought to market. In addition,

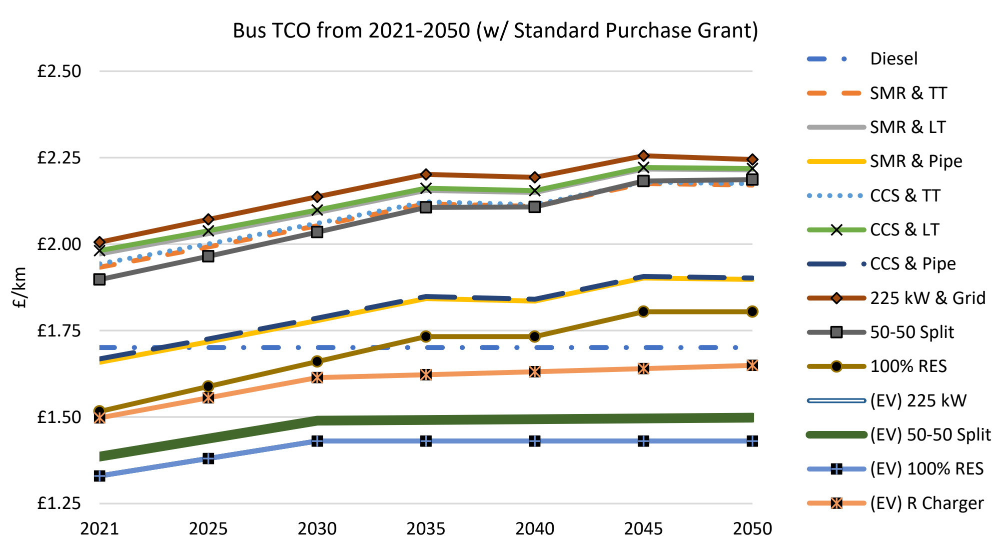

Figure 20. Bus TCO from 2021-2050 with a standard purchase grant added.

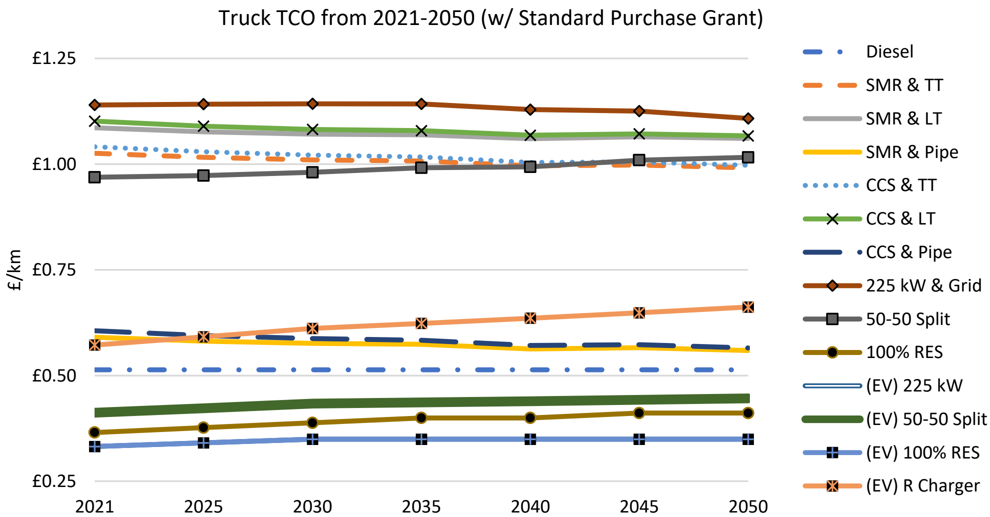

Figure 21. Truck TCO from 2021-2050 with a standard purchase grant added.

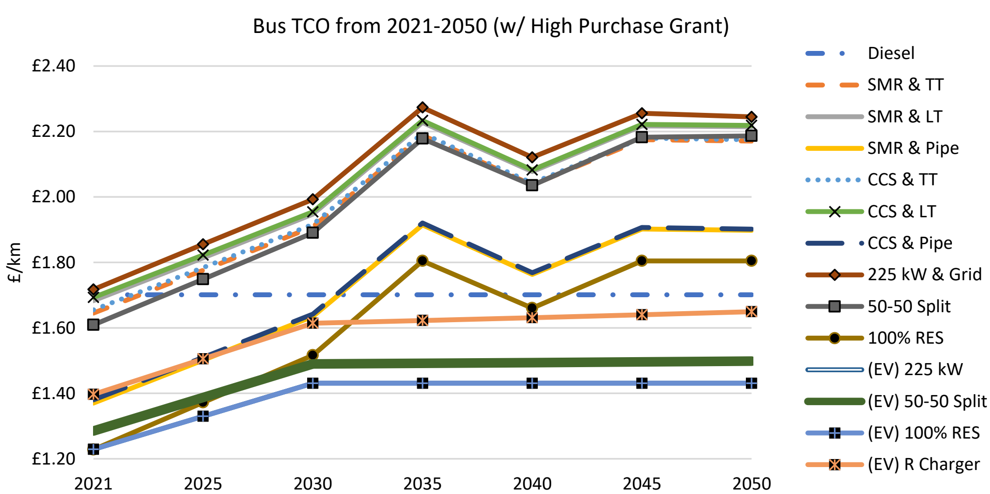

Figure 22. Bus TCO from 2021-2050 with a high purchase grant added.

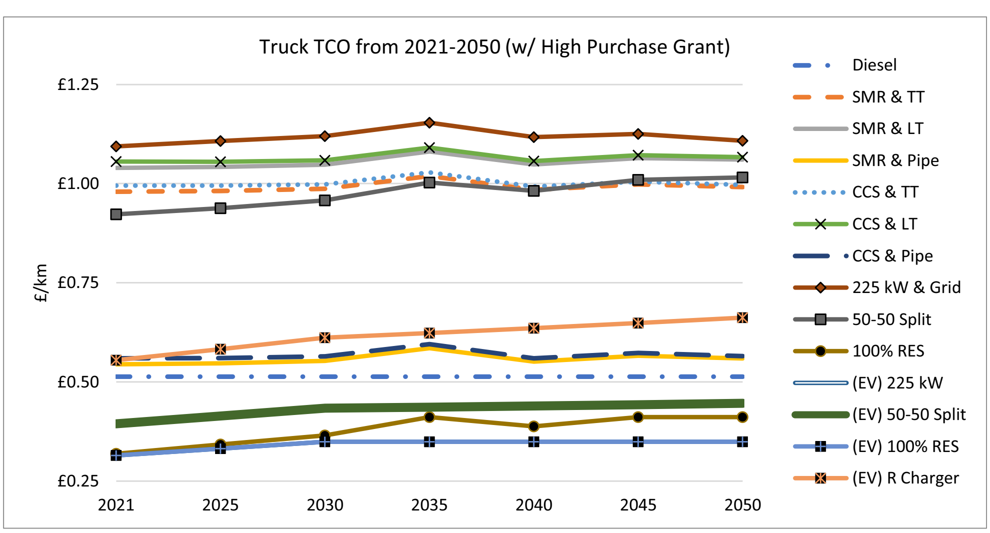

Figure 23. Truck TCO from 2021-2050 with a high purchase grant added.

FC will vary constantly with dynamic driving conditions and vehicle payload, for example. Therefore, a variable FC should be used to take these into account and ensure more accurate costs are calculated which more closely represent real world driving. Similarly, cold weather can significantly reduce battery efficiency, increasing energy consumption and the requirement for charging which could negatively impact fleet productivity. This could be considered in future work using a variable figure which more accurately represents real world driving.

- Sensitivity Analysis: This could be expanded further to consider the impacts of other variables on vehicle TCO. This work examined five parameters, but more could be added to improve the level of detail. For example, different battery chemistries for ZEVs, other diesel deterrents and/or FCEV grants, different depreciation rates, and varying vehicle mileage.
- Study Location: This study is focused on a UK scenario but also provides a solid foundation for the estimation of vehicle and fleet TCO in other geographical regions with methodologies that can be easily expanded and adapted further. This would increase the accuracy of the results and make them more applicable to a wider audience. The inclusion of country-specific government grants and electricity grids for example, could add a new level of detail to both the analysis and discussions.
- Non-Financial Costs: Although TCO focuses on financial costs associated with owning and operating a vehicle or fleet, the work could be improved by making more effort to quantify wider non-financial costs and highlight their impacts. These may include payload losses from batteries, productivity losses due to charging times for BEVs, and changes to operating routes (and therefore mileage) based on the location of refuelling stations/charging points, for example.

5. Conclusions

This paper conducted a TCO analysis on heavy duty on-road and off-road vehicles powered by hydrogen, electricity, and diesel. The results showed that for all vehicles considered in the study, the lowest TCO recorded in 2021 under base case conditions used electricity as the power source, suggesting BEV technology powered from renewable sources offers cost advantages over electrolytic and non-electrolytic hydrogen powered vehicles, as well as diesel. However, a number of hydrogen powered vehicle types still offered a lower TCO than diesel in 2021. These included buses, trucks, tippers, and forklifts using hydrogen from 100% RES hydrogen generated on-site.

Results from the sensitivity analysis show all vehicle types have the potential to become more cost competitive than diesel if using hydrogen from 100% RES as their fuel, with several other hydrogen fuels also leading to lower TCOs than ICEV and even BEV counterparts in some cases, when subject to specific hydrogen-based conditions like fuel price reductions and purchase grants. Both a high purchase grant and low hydrogen fuel price can significantly reduce FCEV TCO from the base case, though for the majority of vehicles, all electricity scenarios except for electricity from a rapid charger remained a cheaper option in terms of TCO. Under a high purchase grant and a 20% fuel price reduction, several hydrogen fuels gave a TCO below diesel, with some FCEV scenarios also falling below BEVs. This highlights the fact that FCEVs have the potential to be the lowest cost option for HDVs when the conditions are favourable for hydrogen. A similar pattern was observed on TCO when ownership period increased.

By 2050, FCEVs running on a number of the hydrogen fuel scenarios will have a TCO lower than diesel, but for the majority of vehicles considered, BEVs remain the lowest in cost per km, unless specific FCEV incentives are implemented. For buses and trucks, the year in which many FCEV TCO scenarios become cheaper than diesel is significantly shortened with the addition of a fossil tax, though this does not impact BEVs which still remain more economical. Despite BEVs appearing to have the lowest financial costs overall, non-financial costs such as reduced payload capacities and long recharging times should also be taken into consideration which may cause disruption to operating patterns and reduce vehicle and fleet productivity, depending on the specific applications. Since FCEVs do not suffer from the same shortcomings, these non-financial impacts may harm the vehicle owner more severely than the additional costs associated with the use of hydrogen vehicles.

Declarations

Author contribution statement

Cameron Rout: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Hu Li, Valerie Dupont, Zia Wadud: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interests statement

The authors declare no competing interests.

Additional information

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